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Volume 15 Sept., 1950 Supplement

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THE JOURNAL OF SPEECH AND HEARING DISORDERS

Volume 15 September 1950 Supplement

American Speech and Hearing Association Annual Directory

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NOTICE TO AUTHORS

Before submitting manuscripts for publication authors should consult Information for Contributors to the Journal of Speech and Hearing Disorders, *JSHD,* 1949, 14, 93-94. Prospective authors are invited to write the Editor for copies of this Note, and of its supplement, Examples of Manuscript Form.

THE AMERICAN SPEECH AND HEARING ASSOCIATION

The American Speech and Hearing Association is a professional and learned association with a current membership of 1623. Begun originally as the Society for the Study of the Disorders of Speech, the organization became the American Speech Correction Association in 1934, and assumed its present name in 1947. Formal annual conventions have been held since 1925, and membership records have been kept since 1926.

The Association publishes *The Journal of Speech and Hearing Disorders*, a quarterly, which was issued first in 1936 as *The Journal of Speech Disorders*, and appeared under that title through Volume 12 for 1947.

Qualifications for membership are set up by the members. All individuals listed in this Directory have been investigated by the Council of the Association in regard to these qualifications and have agreed to follow the principles of ethics found in the Constitution and By-laws of the Association as revised in 1943.

Associate Members (812). Associate Members are persons qualified on an ethical basis who have not, however, completed a professional education in the field of speech correction (and are therefore not recommended as qualified by the Association to do speech corrective work beyond the apprentice level). Dues are $3.50 per year.

Clinical Members (566). Clinical Members are persons with a B.A. degree and one year of experience, who have completed a minimum of special preparation to the extent of 18 semester hours in the field and 12 hours in allied subjects, and who are qualified to act as clinical technicians under the guidance of more completely trained individuals. Dues are $5.00 per year.

Professional Members (147). Professional Members are individuals with four years of postgraduate experience and with relatively complete professional training in the field, and possessing at least an M.A. degree. They are recommended by the Association as being qualified to diagnose and examine cases of speech defects, supervise others in the correction of defects, and to teach others in the arts and skills of speech correction. They are, in short, fully qualified persons upon whom reliance can be placed in the correction of speech disorders. Dues are $12.50 per year.

Fellows (98). Fellows are individuals who have completed professional education in the field, meet all the qualifications of Professional Membership, and in addition have made significant and worthy contributions to the field in the way of research publications. The Association honors such individuals by electing them to Fellowship within the Association. The Association elevates to Honorary Fellowship individuals whose major training has been in an allied field but who have also made significant and worthy contributions to the field of speech correction. Dues are $12.50 per year.

Complete details on application for membership in the Association may be obtained by writing to Secretary-Treasurer George A. Kopp, Department of Speech, Wayne University, Detroit, Michigan.

PATTERN OF PROFESSIONAL GROWTH

The following table shows the growth of membership. The record for years 1926 through 1935 is taken from the individual dues payment records for those years; for 1936 from cash book entries for that year; for the following years from the Membership Directories, published in the *Journal of Speech and Hearing Disorders* (formerly the *Journal of Speech Disorders*) 1937 through 1949.

MEMBERSHIP IN THE AMERICAN SPEECH AND HEARING ASSOCIATION
(Formerly the American Speech Correction Association)

	Associate	*Clinical*	*Professional*	*Fellow*	*Total*
1926	*3*			*19*	*22*
1927	*3*			*19*	*22*
1928	*3*			*19*	*22*
1929	*2*			*23*	*25*
1930	*2*			*23*	*25*
1931	*2*			*27*	*29*
1932	*9*			*28*	*37*
1933	*25*			*27*	*52*
1934	*20*			*37*	*57*
1935	*53*			*34*	*87*
1936	*72*			*43*	*115*
1937	*125*			*60*	*185*
1938	*176*			*72*	*248*
1939	*190*			*61*	*251*
1940	*261*			*69*	*330*
1941	*302*			*72*	*374*
1942	*409*			*72*	*481*
1943	*496*	*5*	*13*	*73*	*587*
1944	*451*	*31*	*24*	*78*	*584*
1945	*498*	*65*	*47*	*74*	*684*
1946	*488*	*120*	*67*	*83*	*758*
1947	*606*	*213*	*84*	*91*	*994*
1948	*603*	*340*	*99*	*102*	*1144*
1949	*816*	*389*	*126*	*101*	*1432*
1950	*812*	*566*	*147*	*98*	*1623*

OFFICERS AND COMMITTEES

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President-Elect.....M. D. Steer, Ph.D., Purdue University
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Gordon E. Peterson, Ph.D. (1950-52).....Bell Telephone Laboratories
S. Richard Silverman, Ph.D. (1949-51).....Central Institute for the Deaf
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Standing Committees

(Note: Italic indicates ex-officio members)

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Sara Stinchfield Hawk	1939-40
Samuel D. Robbins	1941-42
Bryng Bryngelson	1943-44
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Herbert Koepp Baker	1947
Martin F. Palmer	1948
D. W. Morris	1949
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Secretaries

Sara Stinchfield Hawk	1925-30
Samuel D. Robbins	1931-40
D. W. Morris	1941-48 (June)
George A. Kopp	(July) 1948

MEMBERSHIP LIST, 1950

The following alphabetical lists of members of the Association give the title, degrees, professional rank, and address of every Fellow (F), Professional Member (P), and Clinical Member (C), and the address of every Associate Member whose dues for the current year were paid by January 15, 1950 in accordance with Section 4 of Article IV of the Constitution as amended at the 1942 Chicago Convention. **This is not a complete list of members.**

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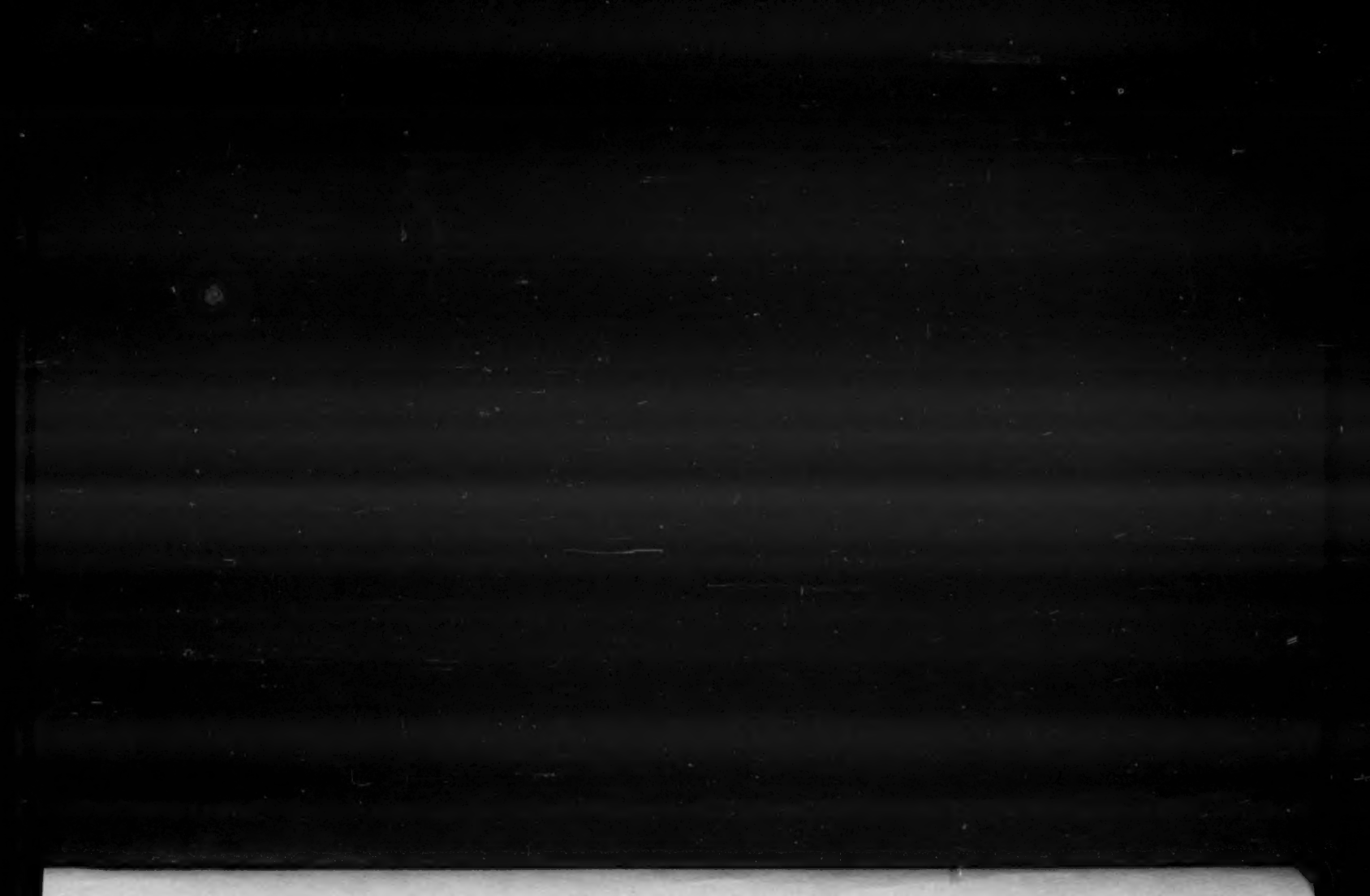

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THE EFFECTS OF NOISE ON MAN

Karl D. Kryter

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Research Laboratories

Bolling Air Force Base

Washington, D. C.

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FOREWORD

THE PUBLICATION of this *Monograph Supplement* to the *Journal of Speech and Hearing Disorders* is a new venture. Several years ago it became apparent that long articles could not always be accommodated satisfactorily within the *Journal* proper. A major purpose of the present monograph, for example, would not have been accomplished had it been divided and issued piecemeal over several years. To meet this situation the Executive Council of the American Speech and Hearing Association authorized the Editor and Business Manager to proceed with a series of *Monograph Supplements* as suitable manuscripts or groups of manuscripts were submitted, and as the *Journal's* financial status made their publication possible.

The Effects of Noise on Man is a review, summary, synthesis, evaluation, and interpretation of the experimental literature on noise as an aspect of man's environment. Its first section is concerned with effects upon behavior, particularly in regard to work output and efficiency. The second part brings together material on auditory damage as the result of noise, and defenses against such damage. The third portion considers noise as a disruptive factor in speech communication. A bibliography on methods of noise measurement and procedures for reduction is added as an appendix. The breadth of the project is indicated by the fact that more than 650 different titles are included in the chapter bibliographies and appendix.

On the subject of noise and men the author, Dr. Karl D. Kryter, is an authority at the experimental level. An experimental psychologist who has specialized in psycho-acoustics and psychophysiology, he has published approximately 20 reports of experimental investigations relating to the effects of noise upon speech communication and audition, and has also done considerable electro-physiological research on functions of the higher acoustic nerve centers in animals. Following graduate study which led to the Ph.D. degree in psychology at the University of Rochester, he was a Fellow of Harvard University, where he was associated with Psycho-Acoustic Laboratory during and immediately after World War II. From 1946 to 1948 he was Assistant Professor of Psychology at Washington University and Research Associate at the Central Institute for the Deaf. Since 1948 he has been Director of the Human Resources Research Laboratories, Headquarters Command, United States Air Force, where he has continued work upon psychological problems of human communication.

The *Journal of Speech and Hearing Disorders* presents this author and his work with pride. Appreciation of noise as an interferer and a producer of disorders in speech communication is widening. The interest in acoustic hygiene, especially in industrial and military circles, mounts steadily. It is appropriate to take a careful look at the fundamental experimental evidence.

Grant Fairbanks — July 1, 1950

PREFACE

IN 1948 THE AUTHOR undertook the task of preparing for the Bureau of Ships, under a contract between the Office of Naval Research and the Central Institute for the Deaf, a report that would summarize in as succinct a form as possible the literature on the effects of noise on man. The final report was envisaged as a sort of brief 'handbook' that might be of assistance to engineers in the design and instrumentation of communication systems and work spaces subjected to intense levels of noise. Inasmuch as the 'human operator' is not, at least so it seems to the psychologist, adequately considered and often little understood by the engineer, the job of preparing such a report was eagerly undertaken. In addition, during the war years, particularly in the field of psycho-acoustics, much research had been accomplished which could be discussed and applied with benefit to the art of engineering.

The final aim of the report, however, became more general than a summarization of experiments conducted in the military and industrial situations. An attempt was made to dig as deeply as necessary into basic psychological and physiological experiments to support and elucidate the results of the 'applied' and technical research. It perhaps should be pointed out that all of the literature included in the report for discussion appears either in professional journals or in unclassified and declassified government publications. Also, the scope of the report was not confined in any way to consideration of military problems.

The report is divided into three major parts: (1) Effects of Noise on Behavior, (2) Deafening Effects of Noise, and (3) Effects of Noise on Communication by Speech. Each part of the report is followed by its own biblography and, in addition, there is attached a bibliography concerned with 'Measurement and Reduction of Noise.' This attachment represents titles accrued during the search through related literature and is included for what it may be worth to the interested student.

The bibliographies of the report represent a joint effort of Mr. Morris C. Leikind and Mrs. Mabel H. Eller of the Navy Research Section of the Library of Congress and the author. Verification of titles and editing was done by Mrs. Eller and Mrs. Virginia Boteler of the Library's staff. Grateful acknowledgment is given to staff of the Navy Research Section of the Library of Congress; through their efforts the references are much more extensive and accurate than would have been otherwise possible.

Appreciation is also due to the many authors and journals for permission to reproduce the figures in the report. Finally, the author wishes to express his gratitude and indebtedness for the guidance and patience of Dr. Hallowell Davis of the Central Institute for the Deaf, under whose supervision this report was prepared. His knowledge of the entire subject matter, suggestions and editorship were invaluable in bringing the report into its final form.

INTRODUCTION

SINCE THE ADVENT of power driven machinery, man has been beset with the obnoxious effects of noise or 'unwanted sound.' Although it had long been recognized that noise may be present in injurious amounts in some industries, the possibility that the noise on battlefields and aboard planes and warships might interfere with military efficiency directed a new interest to the question of noise control during World War II. The magnitude of the problem can be illustrated by the following example: Tests reveal that with the communication equipment used during the first years of the war, less than 30% of special test words could be correctly heard over the interphones aboard bomber planes and in engine rooms of warships because of the intense, continuous, ambient noise. Besides interfering with the understanding of speech, noise and gun blast contributed to the partial or complete destruction of the hearing of several thousands of military personnel.

In general, the effects of noise on man's health, other than hearing, and behavior have been exaggerated and what effects there are have often been misconstrued. For one thing, a line must be drawn between the effects of sharp, sudden noises or sounds and steady-state (continuous) or regularly intermittent noises. The former possess a characteristic of unexpectedness causing a fright reaction which is, of course, not unique to noise stimuli, but applies equally to sudden visual and tactile stimulation. There has been a tendency to overlook the rather innocuous effects of noise that have become a 'regular' part of one's environment, and to emphasize the drastic effects of the blast of an auto horn or an unexpected bang of a door. Although mention will be made later of the effects of sudden, unexpected sounds, the discussion will be centered on steady-state and regularly repetitious noises in that (a) they are the rule in the industrial and military environment, and (b) experimentation, particularly on work output, has been concerned with this type of noise.

Before entering the discussion, mention should first be made of the fact that it is difficult to define noise in terms of any of the physical parameters of sound waves, such as complexity of wave form or intensity. For example, both music and pure tones under certain conditions are commonly considered as noise; the most acceptable definition of noise is apparently that of 'unwanted sound.'

Part 1 EFFECTS OF NOISE ON BEHAVIOR

THE EFFECTS of noise on the mental and motor activity of man have been the subject of many articles and a considerable number of research projects. Industrial management has been extremely interested in the general problem since it has seemed possible that both office and factory noise might have a detrimental effect upon production and personnel efficiency; the military were concerned with the possible effects of noise upon personnel while flying an airplane for long periods, and upon speed and accuracy in aiming guns and fire-control directors; public health authorities were fearful of the consequences of the noises of daily living upon the health of the populace.

The present discussion will be confined to a survey of the effects of noise on work and other behavior that does not require auditory communication for its completion. Such activity might be termed 'non-auditory behavior.'

Viewed from a scientific aspect, a great number of publications in this field represent poorly designed experiments or unsupported opinions. There have been, of course, some outstandingly good studies. Many results that may seem insignificant are included in the following discussion for purposes of criticism and for the sake of completeness. This seems advisable because certain unreliable observations are quoted in the literature again and again without adequate comment regarding the experimental procedures employed in their attainment.

The papers will be divided, for ease of presentation, into (1) industrial field studies, (2) laboratory experiments concerned with work output and accuracy, (3) feelings of annoyance, (4) physiological reactions to noise, (5) public health and noise, and (6) effects of extreme intensities.

Industrial Field Studies

Kornhauser (*40*) attempted to determine whether typists working in a relatively quiet office do more work and feel less fatigued than those working in a noisy office. (It will be noted in this and many of the experiments to follow that 'noise' is described only qualitatively, making comparison of results among experiments difficult.) Record was kept of (a) two typists who spent the first two days working in a quiet office and then two days in the 'noisy' office and (b) two other typists who worked in the reverse order of noise and quiet. The results showed that wasted lineage was 23% greater in the quiet room than in the noisy room, and also that 1.5% more lines were written under the noisy conditions. Rating scales revealed that the girls felt they were working harder in the quiet than in the 'noise.' The differences between the two conditions cannot be accepted as necessarily significant, because of the small number of subjects. But the most important criticism against this study, and the one that can be leveled at nearly all the 'experiments' conducted on this problem under actual working conditions, is that there could have been many differences between the two work offices other than noise level, such as lighting, ventilation, etc., that might account for the results.

There are some reports that purport to show a deleterious effect from noise. It is claimed, for example (*3*, *45*, *47*, *52*), that 'moving the assembly department of a regulator company from adjoining a noisy boiler shop to a quiet room resulted in lowering rejections at inspection from 75% to a

low figure of 7%.' The conclusion drawn was that the reduction in noise level caused the increased efficiency. Changes in lighting, temperature, facilities, etc., were again ignored as possible contributing factors. In spite of the numerous articles published on these results there are no references to the original study other than the statement that it was done by a 'Dr. Sachsenberg' in Germany (*45*).

Major Field Studies. It is apparent that 'on the job' studies of work output, fatigue and the like are made exceedingly difficult and suspect by many uncontrolled conditions. Before turning to experiments conducted in the laboratory, however, mention should be made of two studies, one British, the other American, that represent probably the best, most carefully prosecuted 'on the job' researches on this problem.

1. Weston and Adams studied in Britain the effect of noise on the work performance of weavers (*99, 100*). The looms in weaving sheds create a considerable din which registers 96 db (probably re .0002 dyne/cm^2) on a sound level meter. Weston and Adams did three experiments: (1) they had 10 weavers wear ear plugs, which reduced the intensity of the noise at the eardrum by 10 to 15 db[1], on alternate weeks and recorded their output over a 26-week period, (2) they equated two groups of weavers, 10 in each group, with regard to past efficiency; then one group wore ear plugs while working for a six-month period while the second group served as a control, working without ear plugs, and (3) they repeated the second experiment, using some different subjects, but extended this experiment over a period of one year.

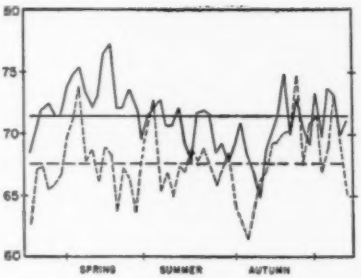

FIGURE 1. Comparison of weekly outputs of weavers during one year. Experimental group, noise subdued by earplugs, unbroken line; control group, normal shed noise, broken line. From Weston and Adams (*100*), with permission of the Controller of His Britannic Majesty's Stationery Office.

The results of all three experiments were roughly the same—about a 12% average increase in efficiency for those who wore ear plugs with respect to those who did not. The gain amounted to a 1% increase in the amount of material produced. The results of the first experiment were considered suspect by Weston and Adams, however, because of a difference in humidity between the weeks worked with ear plugs and the weeks when ear plugs were not worn.

Figure 1 shows the results of the third experiment. It is to be noted that towards the end of the year the experimental and the control groups were coming closer together with regard to work output. This suggests that an initial difference in motivation between the two groups might have helped make the experimental group superior and the control group inferior. But as the experiment wore on, it might be surmised, the added motivation or interest from being a

[1]The decibel (db) is a common unit that can be used for expressing the ratio of two amounts of sound pressure. Number of decibels $= 20 \log_{10} \frac{\text{Pressure 1}}{\text{Pressure 2}}$.

subject began to wane, bringing the control and experimental groups closer together with regard to the work output. Indeed, the subjective reports of some of the subjects indicate an approval of experiments and attempts to help the worker. It is well known that such attitudes alone can result in significant changes in work output, in the presence of noise (*6*). Another critical point has been made by Berrien (*11*) who noted that the equality of the control and the experimental groups in the first and second experiments was never demonstrated.

It is possible that in spite of these shortcomings in experimental procedures the results are correct, but they must be accepted with reservations.

2. The major American field study was conducted by the Aetna Life Insurance Company in its own offices. Apparently it has never been published in its entirety, although sample results have appeared several places (*47, 52, 101*). Semi-monthly bonus figure records for typists, clerical checkers, punchcard and comptometer operators were compared for a year prior to, and a year after sound absorbing material was installed in all offices. As a result of the 'quieting,' calculating machine operators' errors were reduced 52%, typists' errors 29%, health improved 37.5%, and employee turnover was reduced 47%. A truly remarkable achievement for absorbent wall board! The sound level was reported as about 41 db[2] prior to the sound treatment and 35 db after.

In view of other studies, these claims are fantastic when accredited, as they are, to 'adjustment of the noise factor alone.' Because of a paucity of relevant facts, it is difficult to criticize the study, but one obvious factor undoubtedly contributing to the differences between the variables recorded was the lapse of time. Two years elapsed in which the workers may have improved their efficiency through learning; the ill and non-adept may have changed jobs, etc. One control check was made a year later which should, by itself, provide ample data for negating the conclusion concerning the effects of noise. For this check the sound-absorbing walls were covered with gypsum board, thereby raising the sound level by 6 db. The bonus efficiency dropped to some extent (not as low as the first year), but within two months was as high as the level of the 'quiet' year!

General Conclusions from Field Studies. The evidence, then, from industrial surveys and tests does not convincingly show that the noise encountered in these industries and offices has any detrimental or beneficial effect upon non-auditory tasks performed by man. In none of the studies is evidence presented that workers complained of the noise although there were expressions of approval when 'quiet' was accomplished.

Any tasks involving communication, talking and listening, however, will be interfered with by noise. In this case, noise could be expected to arouse resentment and feelings of annoyance, as well as cause inefficiency. As far as the present author knows, no study involving psycho-motor 'work' in which the variable of communication was studied or held constant has been reported. Speech com-

[2] In the Aetna and many other studies herein presented, the reference for db expressions of noise levels is not given. In most cases it appears likely that the reference level is probably .0002 dyne/cm^2, although in the Aetna study this would make the noise levels unusually low for an office. In this monograph the reference level is given whenever it was reported.

munication did not appear to play a significant role in any of the jobs involved in the papers discussed thus far, although some of the work in the Aetna study may have required some communication.

Laboratory Experiments Concerned with Work Output and Accuracy

Scientists, in attempts to determine the role of noise in non-auditory behavior, have found it necessary to study its effects in the laboratory in order to avoid the mass of other contributing conditions present in the factory or office. It is readily accepted that 'real life' conditions are not met in the laboratory, but if the effects of noise are not demonstrable in the laboratory it is safe to say that startling effects attributed to noise in industry are the result of a combination of other factors.

The results of the laboratory studies are more readily interpreted than 'field' investigations, but unfortunately even here there are some experiments that are equivocal.

Effects of Distraction by Noise on Reaction Time. Most of the early studies on the effects of noise dealt with effects on reaction time (*17*, *28*, *89*). Fairly representative of these early studies is one by Cassel and Dallenbach (*16*), who studied the effect of auditory distraction upon reaction time to various visual stimuli. For 'noise' they employed a sound hammer striking an anvil near the subject. Noise was presented (a) continuously during both reaction and rest periods for some tests; (b) continuously, but only during the reaction periods for another series; and (c) intermittently, but only during the reactions proper for a third set of tests. Cassel and Dallenbach summarize their results as follows:

(1) The effect of distraction upon the sensory reaction is equivocal. The distractor may inhibit and lengthen the reaction; it may facilitate and shorten the reaction; or it may become habitual and have no effect at all.

(2) The effect of the distraction is dependent (a) upon the temporal relations of the distractor, and (b) upon the conscious attitude of the observer during the distraction.

(3) The distractor most resistant to habituation is the intermittent; the least resistant is the continuous.

Effects of Distraction by Noise on Learning. Morgan (*64*, *65*) published in 1916 and 1917 the results of experiments on the effects of distraction by sound on learning. He had subjects learn paired associates consisting of three-letter words and digits in quiet and also when a buzzer and a fire gong were intermittently sounded. The noise interfered slightly with learning, more at the beginning of the experiment than near the end. He also found that in the noise the subjects exerted more muscular effort in manipulating the experimental apparatus and breathed harder than they did in the quiet. Morgan concludes that (1) there is some adaptation to the noise and (2) increased tension and effort can compensate for the effects of the distracting noise so that work output may not be lowered or may even be increased.

Effect of Distraction by Noise on Intelligence-Test Scores. Tinker (*90*) and Hovey (*35*) administered intelligence tests under noisy (intermittent bell) and quiet conditions to large groups of subjects. The noise had no detrimental effect, as revealed in test scores, although in Hovey's experiment the noise had some, but not a statistically significant, deleterious effect (*81*).

Effects of Noise on Mental and Muscular Work. Since it appeared that distraction, due to repeated applications of noise in terms of its effects on reaction time, simple learning problems and intelligence-test scores, was negligible, investigators turned to measuring work output on various mental and muscular tasks on the assumption that noise, if it did not disrupt activity by being distractive, required a greater expenditure of effort that would lead to fatigue and reduced efficiency. The results of these studies appear to be contradictory; a number demonstrated reduced efficiency because of noise, while others proved that noise does not reduce efficiency and may even increase it.

1. Studies Showing a Deleterious Effect. a. Laird (*45*) attempted to measure the oxygen consumption of typists when working in a room with hard surfaced walls and, then, when the walls were covered with a sound absorbing material. Noises generated by ball bearings rotating in a sheet iron, hexagonal drum, a siren, and a telephone bell all operating intermittently and automatically, were present throughout the tests. Laird found a 4.3% increase in speed when sound absorbing material was applied to the walls; error scores remained the same. 19% more oxygen was consumed (the subjects breathed through a metabolism-measuring device during all the tests) when the walls were bare than when covered with sound-absorbing material. No statistics are presented whereby the increased speed can be tested for significance and only four subjects were used. Laird concludes that because of the increased effort on the part of the subjects when in the reverberant room, the effect of the noise was less detrimental than expected, and greater fatigue must be the result if workers keep up production in noise.

Harmon (*29*) criticizes Laird's metabolism data, pointing out the lack of proper controls and of an adjustment period to the metabolism machine. He considers Laird's study as 'suggestive, and little more.'

b. Hsiao (*36*) reports that 'noise' caused a 5.6% decrease in speed, and an increase of 26.6% in wrong answers in the multiplication of numbers for a 10-minute period by grade school students. The noise tests were conducted first, however, followed eight days later by tests in the quiet. It is possible that practice effects alone could account for the finding. The length of test was also very short.

c. Luckiesh (*55*) obtained a statistically significant increase in time required (.82 vs .77 minutes) to take the General Electric 'Demonstration Visual Test' in a noisy generator room in a factory over a quiet room. The work was done in a booth, in both situations, with the level of illumination controlled.

d. Laird (*49*) set up an 'experimental factory' employing two workers at a time. The workers inserted an electrical stylus in small holes as they appeared in a moving tape and record was kept of work done. The workers, all college students, were paid 40c an hour and worked four and one half hours each afternoon. Noise from a 3-A Western Electric Audiometer was amplified and presented to the workers by loud speakers at a number of intensity levels. Each of four workers worked for three months. No individual results or daily records are presented, but we are told that records for 'humid days, hot days or days when one of the subjects felt indisposed are also not included.'

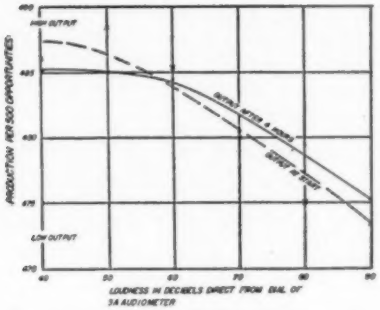

FIGURE 2. Production output at dexterous repetitive work under various intensity levels of complex noise. From Laird (*49*), with permission of the author, the American Psychological Association and the *Journal of Applied Psychology*.

Figure 2 is taken from Laird's report of this experiment. Two things are apparent: (1) in loud noise production increases with time, suggesting a daily adaptation; Laird (*46*) previously held that fatigue from noise should lower work output, (2) the more intense the noise, the greater the initial decrease in production. Laird states that as a precaution against the subjects not being used to the noise, the data for the louder noises were obtained last in the course of the experiment. This experimental procedure vitiates the experiment, for it is well known that the motivation of subjects can well decrease from the beginning of a three-month experiment to the end, thereby accounting for the apparent decrease in production with more intense noises.

2. Studies Showing no Deleterious Effect. a. Vernon and Warner (*94*) found an increase in speed in doing arithmetic problems when noise (gramaphone records, bells, whistles, sirens) was introduced after a brief period of adaptation. They also measured oxygen consumption and found little or no increase in consumption when doing arithmetic problems or reading.

b. Harmon (*29*) conducted a study (see Figure 3) of the effects of noise (phonograph record of office and street noise played at 50 to 65 db and 65 to 75 db respectively) on arithmetic computation. Full and careful measures were made of changes in metabolism. He found that the increases in the working values caused by the noises may run as high as 60% during the first days of an experiment, but that when the subject is presented with the same situation day after day, over a period of several weeks, the noise effects gradually disappear and the working values return to normal. It was determined that when a person

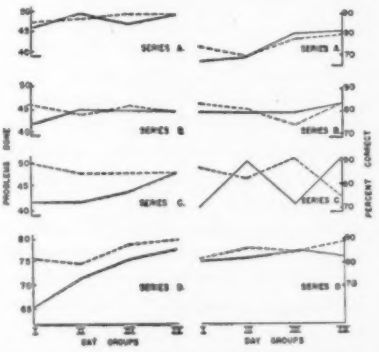

FIGURE 3. Output of one subject in number of multiplication problems done and per cent correct during quiet and noise conditions. Quiet periods, broken lines; noise periods, solid lines. Series A, quiet and noise conditions present on alternate days; Series B, 10-minute work period in quiet, followed by 10-minute work period in noise (office) on each day; Series C, same as B, except street noise; Series D, same as B, except different subject. From Harmon (*29*), with permission of the author, the American Psychological Association, and the *Archives of Psychology*.

became adjusted to a noise level and method of presentation, any change required a brief period of adaptation.

c. A similar result was obtained by Ford (*25*) who found there was an initial slowing up of the speed per problem at the beginning of the noise and again when quiet was restored. In this experiment subjects added sums under quiet, under noise, and again under quiet conditions.

d. Obata et al (*68*) studied the effects of a 'scratching' or grinding noise from a mechanical noise machine and also various types and intensities of music on the efficiency of 24 high school students taking cancellation, addition and transcription tests. 'Mere noise' they found had little effect on efficiency in the tasks studied.

e. A series of well-conducted experiments on the effect of noise were reported by Pollock and Bartlett (72) in 1932. They chose for investigation a number of tests of motor skill, one of which required the subjects to insert in or remove from a rapidly moving platform a small peg when the platform was in a certain position, and a number of 'mental' tasks, such as making as many words as possible from a given group of letters. A number of types of noises were employed, including the sound of 12 heavy printing presses, gramaphone records, clicks presented through earphones, bells, etc.

Proper experimental precautions with regard to sequence of testing in quiet and noise appear to have been observed and adequate numbers of subjects employed. Besides many quantitative measures of performance, subjective impressions of the effects of noise were obtained from the subjects. The conclusions may be summarized as follows:

(1) In general, noise has an adverse initial effect of no great magnitude which rapidly wears off, whether the task be chiefly mental or motor in character.

(2) Discontinuous loud mechanical noises, and 'soft' gramaphone records of music were more disturbing than continuous loud noises, indicating that the disturbance was not simply a matter of loudness.

(3) Subjective reports indicated that a sound could be extremely irritating without lessening the efficiency of performance. Some sounds rated as the most annoying were not also rated as the most distracting.

f. Tests conducted with 'military' noises on psycho-motor efficiency were conducted early in World War II by S. S. Stevens and associates (*87*, *88*). For these tests simulated aircraft noise was generated in a test chamber and its spectra and over-all intensity were measured. Two noise levels were used, (a) 'quiet' level (90 db re .0002 dyne/cm^2) that was loud enough to mask casual extraneous laboratory sounds and to discourage conversation among the subjects, and (b) a 'noise' level (115 db re .0002 dyne/cm^2) that corresponds to about the noise level in the cabin of a typical bombing plane. Five subjects were in the noise continuously for seven-hour periods, for four consecutive days a week, during the major experiments which extended over four consecutive weeks. The 'quiet' and 'noise' conditions and sequence of tests were properly balanced and controlled. It is to be noted that the 'quiet' condition was noisier than the 'noise' condition for most of the other experiments presented. This may, or may not, have been a significant factor determining the results.

In a recent NDRC Summary Technical Report, this work was reviewed by Miller, Weiner and Stevens (see *130*, Part III, this report). They divided the tests into those that gave inconclusive results and those that showed no effect from the noise. The following tests were inconclusive:

(1) Coordinate Serial Reaction-Time. Here the subject manipulated an airplane stick and rudder bar to direct a beam of light at a target following a definite path on a large panel. Each of the subjects made 20,400 reactions in noise and 'quiet.' The reaction in noise was slower by 5.4% and the number of errors was greater by 5.4%. Examination of this test following the completion of the experiment, however, revealed that the subjects when working in the 'quiet' could have made use of certain 'clicks' of timing relays in the apparatus that were not audible in the noise. The experimenters believe, although it was not further tested, that these acoustic clues in the quiet biased the results of this test, particularly since other similar tests showed no effects due to noise. At the time the first report of these findings was made, these extra clues had not been recognized by the experimenters (*87*).

(2) Muscular Tension. This was measured by recording electric potentials from arms and legs of subjects. Although there was some evidence of increased tension in the noise, the records were difficult to interpret because of gross muscular movements that created artifacts in the recordings.

(3) Metabolism. Brief measurements repeated several times during the day indicated that for some subjects there was an increase in metabolic rate in the louder noise, while in other subjects no consistent effects could be noted.

(4) Breathing. Noise caused some, but not all, subjects to breathe more rapidly and less deeply.

(5) Speed of Accommodation. The speed with which the eye can change focus from a near to a distant object and vice versa was reduced by long exposure to noise, but individual differences prevented any generalizations.

(6) Saccadic Eye Movements. The speed with which the eyes could be moved through an angle of 37 degrees was reduced by the noise for one, but only one, of four subjects.

(7) Body sway. The ability of subjects to stand erect without swaying was measured by an ataxiameter. No particular relationship between steadiness and noise was discovered.

(8) Hand Steadiness. The subjects were periodically required to hold a small stylus in the center of a small (3 mm) hole without touching the walls. The noise resulted in a slight increase in steadiness, apparently by 'insulating' the subject from any distractions in his environment.

(9) Reversible Perspective. The subjects were asked to fixate a reversible figure and to press a key at the occurrence of each voluntary reversal. Any relationship between this visual phenomenon and noise was obstructed by variability.

(10) Dark Adaptation. No conclusive effects of noise on the threshold of visual illumination were obtained.

The following tests are not inconclusive like the ones mentioned above, but are positive in their proof that man *can* maintain the *same* levels of performance for these seven tasks in the noise as in the 'quiet.'

(1) Coordinated Serial Pursuit. In this task the subject was required to adjust, by means of airplane controls, the position of the spot on a cathode-ray oscilloscope and the position of a pointer on a direction meter. Graphic records were kept of each of the three dimensions of movement. The performance of the subjects was unimpaired by the noise.

(2) Serial Disjunctive Reaction Time. The ability of the subjects to press a key with the appropriate hand or foot, depending on which of four lights was illuminated in front of him, was absolutely unimpaired by the noise. Each subject made 24,480 reactions in noise and the same number in 'quiet.'

(3) Fast-Speed Pursuit Rotor. Here the subject was required to follow with a stylus a small disk near the edge of a phonograph turn table revolving 99 rpm. The noise had no effect.

(4) Card Sorting. The ability and speed of sorting 12 kinds of cards into 12 compartments was maintained in noise as well as in 'quiet.'

(5) Coding Test. The subjects translated written material into code as rapidly in noise as in the 'quiet.'

(6) Judgment of Distance. Monocular judgments of distance, measured by the ability of the subjects to adjust the distance of a movable wire to match the distance of a comparison wire, were unaffected by the noise.

(7) Subjective Experiences. The subjects filled out daily questionnaires regarding their feelings and uniformly expressed preference for the 'quiet' days. There was an inconsistent tendency to report greater feelings of fatigue at the end of the experiments in noise than in 'quiet.'

It was concluded from this review that airplane noise has no, or at the worst, but slight detrimental effect upon motor coordination, reaction time, sensory perceptions, and certain mental functions even after exposures lasting seven hours. Nevertheless, all the subjects expressed a preference for the quiet over the noise conditions and tended to report subjective feelings of greater fatigue and irritability after being subjected to the noise.

g. Another experiment which was conducted with respect to the military situation dealt with effects of loud sounds on the accuracy of azimuth tracking and stereoscopic range finding with a gun-fire control device (*91*). In this experiment, operators were subjected to phonographically recorded sounds, such as air-raid sirens, exploding bombs, and airplanes. The results were summarized in one report (*91*) as follows:

> Experiments at Tufts College and Brown University reveal that loud sounds (up to 120-130 db) do not produce a decrement in quality in either azimuth tracking or in stereoscopic range finding, within the limits of this experiment. This includes the condition where loud sounds had not been previously experienced and its onset unexpected. Indeed, in the case of azimuth tracking, the introduction of a loud sound, after a four-hour tracking period, resulted in improved performance which lasts for the duration of the sound. Return to the previous level of performance is rapid. Observers report that the sound produced muscular tension, but, nevertheless, was a relief from the monotony and an aid in staying awake.

h. A study was conducted for the Navy by the Research Laboratory of the American Society of Heating and Ventilating Engineers to determine the accuracy and variability of work output of men working in hot spaces with different noise levels (*95*). It

was found that noise had no effect on work accuracy or output, but that noise above 80 and 90 db resulted in feelings of irritability and unpleasantness on the part of the workers.

General Conclusions from Laboratory Tests. The experiments on the effects of noise on mental and motor activity conducted under laboratory conditions can be grouped into three categories:

1. Experiments demonstrating definite deleterious effects of noise. Nearly all, if not all, of these studies can be heavily criticized on one or more points so that their findings can be accepted only with considerable reservations.

2. Experiments demonstrating slight, inconsistent, or inconclusive detrimental effects from noise.

3. Experiments that demonstrate conclusively that man can do muscular and mental work as efficiently and productively in noise as in quiet, even for prolonged periods. For some few tasks, noise apparently improves performance. These findings are explained as follows:

a. Difficult tasks. The subjects concentrate on the task and ignore noise. For some tasks, such as aiming a gun, apparently noise permits a greater concentration of attention than is achieved in average quiet conditions.

b. Easy tasks. Noise does not disturb performance since the task becomes automatized.

c. Voluntary compensation. Subjects work harder because of the noise.

d. Involuntary compensation. Adaptation sets in with continued exposure to a noise so that the noise becomes a part of one's environment. Adaptation to the acoustic environment is possibly a very real reaction that reduces regular or continuous noises that do not reach the thresholds of feeling or pain to a subjective status that precludes their interference with non-auditory activity. One thinks of the way man adapts to changes in light level without interference with psycho-motor activity, and of the story of the lighthouse keeper who gave a startled cry, 'What in the world is that noise?' when the fog horn which he had heard sounding every 30 seconds for 10 years suddenly ceased bleating.

It is to be understood, of course, that these conclusions apply only within the limits of the kinds of noises and tasks employed in the experiments discussed.

Feelings of Annoyance

Mention has been made previously of efforts to secure from the subjects of noise experiments their subjective impressions of the effects of noise and their attitudes towards it.

The annoying value of various noises appears to vary with a number of aspects of the noise. A few of the more obvious are:

1. Unexpectedness. Unexpected noise can elicit certain startle or fright reactions. These will be discussed in a later section.

2. Interference with Auditory Behavior. There have been no systematic investigations of annoyance due to masking.

3. Inappropriateness. The cracking of peanut shells at a concert, music when one is trying to concentrate, etc., are examples. Individual differences and variability make it probably impossible to order sounds or noises on this characteristic with respect to their annoyingness.

4. Intermittency. Cassel and Dallenbach (*16*) found that an intermit-

tent noise resisted habituation more than a continuous sound. Also, Pollock and Bartlett (*72*) found that irregular mechanical noises were always initially displeasing. They found no particular consistent relationship, however, between work output and subjective feelings of irritation due to noise.

5. Reverberation. Sabine and Wilson (*76*) report that the 'spreading' or lack of localization of noise contributes to its annoying quality.

6. Intensity or Loudness. Other things being equal the more intense a given noise, the more annoying it is. (*50, 74*). The intensity threshold at which any sound becomes annoying, however, has not as yet been determined. Half of the workers in Weston and Adams study (*99*) reported a complete indifference to the noise which measured 96 db. Stevens et al (*88*) report subjective feelings of irritability in subjects working in 115 db re .0002 dyne/cm^2 of airplane noise. The same subjects apparently did not report disagreeable effects when they worked in only 90 db re .0002 dyne/cm^2 of airplane noise. Seven out of 10 subjects reported greater than normal feelings of irritability after serving in an experiment requiring them to spend 20 hours over a six-week period in 120 db re .0002 dyne/cm^2 of turbo-jet engine noise (*70*). It was found in another study (*23*) that noises above 80 and 90 db resulted in feelings of unpleasantness on the part of some of the subjects.

7. Frequency pattern. There have been several studies in which sounds of differing spectra were compared with regard to their annoyance. In most of these researches, two sounds were adjusted to equal subjective annoyance and their loudnesses or intensities were then compared.

Laird and Coye (*50*) had subjects adjust the intensity of a number of pure tones until each appeared to be equally annoying as a standard tone of 256 cps. They found that the higher frequencies tended to be more annoying than the 256 cps tone when of supposedly equal loudness.

Reese and Kryter (*74*) found essentialy the same effect when using bands of noise. In this experiment, the bands of noise were equated first for equal loudness with respect to a 'standard' band of noise extending from 1900 to 2450 cps and secondly for annoyance. The results shown in Figure 4 reveal that annoyance is a characteristic of sound that is discriminable from loudness. There is some evidence, however, that subjects become adapted to this characteristic with prolonged testing so that the annoyance and loudness contours become less separated (*44*).

It was found that the reduction of high-frequency components of noise by acoustic treatment of a bomber reduced the annoyance to such an extent that the noise in the treated bomber could be 10 db more intense than the noise in the untreated bomber before they were considered as equally annoying (*88*).

Parkinson and Jack (*69*) report that a variety of actual experiences in acoustic engineering indicate that high-frequency noise requires special attention all out of proportion to its relative intensity.

Perhaps related to the relationship between frequency pattern and annoyance is the fact that high frequencies tend to be more damaging to the ear than low frequencies.

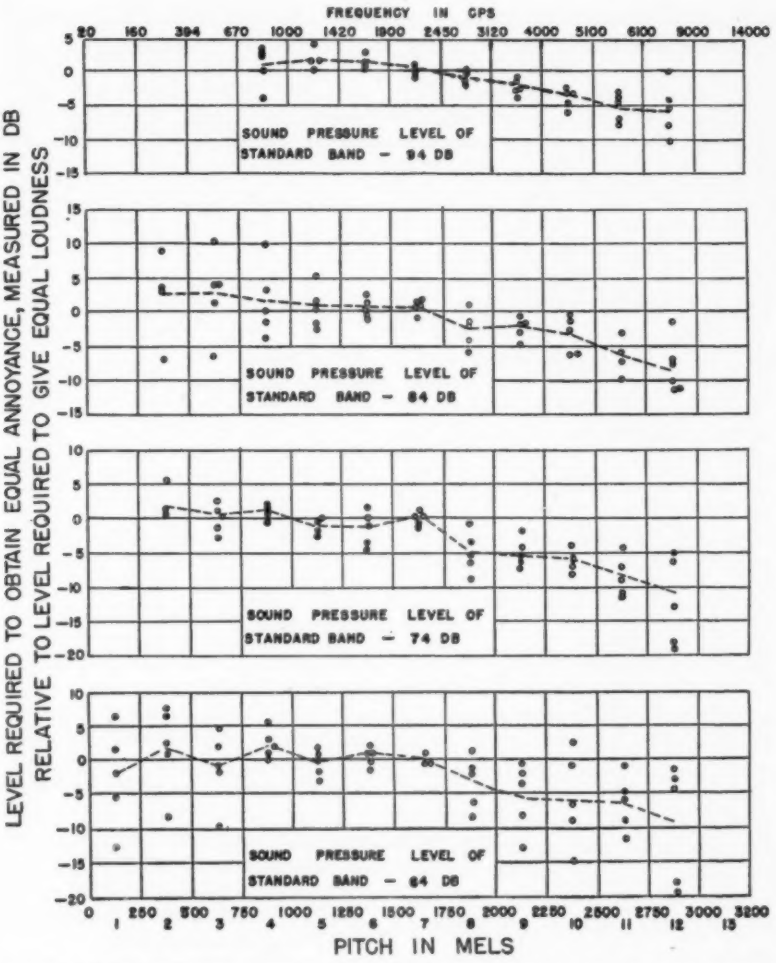
FREQUENCY IN CPS
20 160 394 670 1000 1420 1900 2450 3120 4000 5100 6100 9000 14000
SOUND PRESSURE LEVEL OF STANDARD BAND — 94 DB
SOUND PRESSURE LEVEL OF STANDARD BAND — 84 DB
SOUND PRESSURE LEVEL OF STANDARD BAND — 74 DB
SOUND PRESSURE LEVEL OF STANDARD BAND — 64 DB
LEVEL REQUIRED TO OBTAIN EQUAL ANNOYANCE, MEASURED IN DB RELATIVE TO LEVEL REQUIRED TO GIVE EQUAL LOUDNESS
0 250 500 750 1000 1250 1500 1750 2000 2250 2500 2750 3000 3200
1 2 3 4 5 6 7 8 9 10 11 12 13
PITCH IN MELS

FIGURE 4. Equal annoyance contours for bands of noise 250 Mels wide; Band no. 7 taken as standard. 5 subjects. From Kryter (*44*).

PHYSIOLOGICAL REACTIONS TO NOISE

Brief mention has been made previously of the effects of noise on metabolism. The weight of the evidence appears to indicate an initial rise in metabolic rate because of noise, but with continued exposure there is a return to normal. The apparent difficulty of measuring metabolism precludes any determination of small differences or changes in metabolic rate.

Internal Changes. Davis (*21*) reports an increase in muscle tension and a decrease in the resistance of the

skin to an electric current in the presence of noise. Both return to normal with continued repetitions of noise. Stevens (*87*) found an inconclusive but slight tendency for muscle tension to be greater in noise than in the quiet. Morgan (*65*) also found greater muscular tension in his subjects in intermittent noise than in the quiet.

Smith and Laird (*82*) found a decrease in peristaltic contractions and in the flow of saliva and gastric juices following sudden unexpected noises of 80 and 90 db. Apparently, only two 10-minute periods of noise were presented to each subject so that adaptation to the noise could not have been achieved.

Kennedy (*38*) describes an experiment in which a tambour was placed over skull defects of operated patients and variations of intra-cranial pressure were graphed. A sharp loud report produced a decided rise in intracranial pressure. There is ample evidence (*51, 54*) that a sharp report will cause a general rise in blood pressure.

Many of the above responses can be classed as startle responses to an unexpected or disturbing stimulus. It is to be noted that in those experiments in which the noise became expected, the internal physiological changes returned to normal.

In a recent study, Finkle and Poppen (*23*) exposed 10 men for one-hour periods for 10 days followed by two-hour periods for five days to noise of about 120 db re .0002 dyne/cm^2. The noise was generated by a turbo-jet engine. Numerous physiological measures indicated complete adaptation, for the investigators found that the subjects were normal before, during, and after daily exposure to the engine noise in respect to (a) pulse rate, (b) respiratory rate, (c) blood pressure, (d) basal metabolism, (e) visual acuity, (f) electrocardiograph, (g) electroencephalograph, (h) urinary tests, (i) kidney function tests, (j) sedimentation rates, (k) bleeding and clotting times, (l) icteric indices, and (m) x-rays of chest and abdomen.

Effects on Vision. Of a somewhat different order are some effects of noise or sound upon certain visual functions, such as flicker (*42*), colour sensibility (*1, 43*), accommodation and eye movements (*87*). These effects appear to be so small as to go unnoticed unless measured by extremely accurate methods in the laboratory and the effects may be either inhibitory or excitatory, depending upon the particular function studied and the intensity of the noise.

It is possible that noise may also exert some slight effects upon senses other than vision.

Public Health and Noise

No attempt was made to examine the popular literature on the effects of noise on public health, but a discouraging number of opinions and unwarranted statements on this subject were found in the medical journals. Statements are made that noise is ruining the public health (*5*), that it is filling our mental institutions (*56*), and that since the onset of the industrial revolution, it has caused a steady decline in the birth rate (*71*).

Most of these conclusions are based on generalization and extrapolations from experiments based on short exposures to noises that did not allow adaptation. Adaptation to noises is not recognized in these theories or it is proposed that adaptation to noise is costly. Kennedy (*38*) states, for example, that persons adapted to noise do not realize that 'energy and virtue

[sic] is going out from them, that fatigue is on the way, and that toleration takes its toll.'

Most of the evidence, however, reveals that once adaptation to noise is achieved energy is not expended at a rate significantly greater than normal.

Except as the more or less continuous noises of the factory, office, home and street may damage the ear of man, there is but little evidence of any damage or interference of a physiological sort by such noises, although subjective feelings of annoyance are expressed by some of the people exposed.

Effects of Extreme Intensities

Up to this point, this study has been concerned with noises and sounds encountered in industries, in the planes and other vehicles of World War II and with approximations of them as generated in the laboratories. These noises extended up to about 120 db re .0002 dyne/cm^2. Apparently, man can completely or nearly completely adapt, both voluntarily and involuntarily, to these noises as they continue so that they have little objective effect on his non-auditory behavior. Sounds above that level, however, have certain consequences that are not observable at lower levels. For one thing, the thresholds of feeling, tickle and, perhaps, pain are reached, and these sensations adapt only to the degree that with continued stimulation at high intensities these thresholds will rise 5 to 10 db.

Sound levels as high as 150 db re .0002 dyne/cm^2 have been measured near the exhaust of a turbo-jet aircraft engine (*70*). (The sound levels inside the cockpit of a turbo-jet plane are considerably less, reaching only about 115 db.)

Parrack, Eldredge and Koster (*70*) recently reported the effects on man of turbo-jet engine noise and siren-generated sounds of the order of 150 db re .0002 dyne/cm^2. These effects can be summarized as follows:

(1) Severe but temporary hearing loss.

(2) Heating of the skin. (When rats and guinea pigs were exposed for sufficient lengths of time they died because of increased body temperature.)

(3) At frequencies between 700 and 1500 cps, from the siren or in the presence of the turbo-jet engine, there is a sensation of vibration of the cranial bones, and air movement in the nasal passages and sinuses. Vision becomes blurred, apparently due to vibration of the eyeballs.

(4) An apparent weakening of the body supporting musculature. This is apparently not the result of a true muscular weakness but results from an effect on the proprioceptive reflex mechanism, since with conscious effort one can maintain normal posture.

The investigators suggest that these effects, which have usually been attributed to the action of 'ultrasonic' frequencies present near the turbo-jet engine, are really the result of the extremely intense sound in the audible range.

Finkle and Poppen (*23*) observed the effects in 10 men of the exposure to the noise near a turbo-jet engine. The noise at the positions taken by the subjects reached as high as 120 db, which was not nearly as intense as that generated in the experiments of Parrack, Eldredge and Koster.

General Conclusions

A survey of the literature pertaining to the effects of noise on mental and

motor work in industry and in the laboratory situation and to related studies concerning annoyance and physiological reactions to noise has been made. This survey shows that nearly all industrial and laboratory experiments which report that noise adversely affects work output are open to criticism because of poor experimentation and uncontrolled factors. (By 'work' is meant any mental and motor tasks not involving communication by speech.) On the other hand, experiments carried out with proper control of all pertinent factors reveal that steady or expected noises do not adversely affect psycho-motor activity to any significant extent. As a matter of fact, there is some evidence that noise may 'insulate' a person from intermittent distractions in his environment so that on some tasks, such as aiming a gun, performance is better in noise than in quiet.

The general ineffectiveness of noise on work output and on psycho-motor performance can be largely explained by a psychological and physiological adaptation and perhaps by an increase in effort on the part of the subjects. About 50% of subjects exposed for long periods to intense, and particularly to high-frequency noise, feel that exposure to such noise makes them more irritable than normal. Some comfort is g a i n e d by preventing steady noises from exceeding 90 db re .0002 dyne/cm^2 at the position of the listener. Most persons exposed to intense noise as high as 120 db re .0002 dyne/cm^2 as a matter of course in their work apparently become indifferent to it. Mention is made of certain definite effects of noise when its level is as high as 150 db re .0002 dyne/cm^2.

Although steady-state noises appear to have little real effect on work output, it will have an adverse effect upon communication by speech or other auditory signals, and it has been experimentally demonstrated that the 'annoyance value' of a noise is related to its spectrum. Noises containing the higher frequencies of sound are more annoying than those of predominately low frequencies.

Probably most of the experiments conducted on this problem did not reflect the full impact of noise on the performance of the office and industrial worker in that the studies were primarily confined to non-auditory work not involving communication, whereas communication is required in most occupations. Thus, noise absorption and reduction should lead to greater efficiency and comfort of the office and industrial worker, although most of the experimental results so far have been negative or inconclusive.

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Part II DEAFENING EFFECTS OF NOISE

IT HAS BEEN amply demonstrated that noise may be damaging to the auditory mehanism of man and it is the purpose of the second part of this report to review and evaluate the results of research conducted on this subject. For ease of presentation the literature will be divided into several divisions: (1) Deafness Resulting from Noise, (2) Relationship of Hearing Loss to Social Adequacy, (3) The Use of Ear Plugs, and (4) Problems of Deafness in Military Situations.

The word deafness in everyday terminology is used to indicate only a condition of total deafness wherein a person is unable or almost completely unable to hear sound. In the medical sense, however, the word deafness is applied to all degrees of impairment of hearing from that of a slight deficit to the case of total deafness and of either temporary or permanent duration. In the present report the word deafness is used in the latter or medical sense.

Deafness Resulting From Noise

Even though an otologist as late as 1938 claims credit for first relating industrial noise and a localized hearing loss, the general facts of deafness due to industrial noise were discussed as early as 1831 by Fosbrooke (*61*). Indeed, as has been noted also by Bunch (*14*), Fosbrooke speaks in 1831 of 'old' and 'modern' discussants of this subject. Nevertheless, there have since been numerous studies of the hearing of industrial workers in Europe and America.

Except for Coosemans (*32*) who believed from an analysis of data he collected that industrial noises were harmful only when the worker was predisposed to deafness because of lesions or ear infections, the early investigators of professional deafness, from Fosbrooke on, found what they considered a significant percentage of industrial workers to be deaf. For example, Temkin (*236*), who has published one of the most complete studies on this subject, found that in certain metal-working occupations 83% of the men could not hear a whisper more than 4 meters away and that after 15 years work none could hear a whisper at 4 meters.

Larsen (*128*), in making an exhaustive study of shipyard and factory laborers, employed both the whisper and audiometric tests. He found hearing deficient in about 50% of the men examined. McKelvie (*141*) found with the whisper and voice tests that about 25% of 1001 weavers had some form of deafness.

The early studies clearly revealed that in 'noisy' occupations deafness was common. A number of questions related to industrial deafness, however, such as temporary vs. permanent effects of noise, effects of age, type of deafness and effects of different frequencies and intensities of sound were raised in these studies.

Temporary Effects. McCoy (*137*) compared the hearing loss of men working at metal 'chipping' in 110-130 db (probably re .0002 dyne/cm^2) after seven hours and after one month of exposure (See Figure 1). McCoy states that the hearing loss became slightly greater after six months than after one month of exposure. Although McCoy does not present his data in sufficient detail with respect to number of subjects and period of testing to demonstrate any 'adaptation,' he

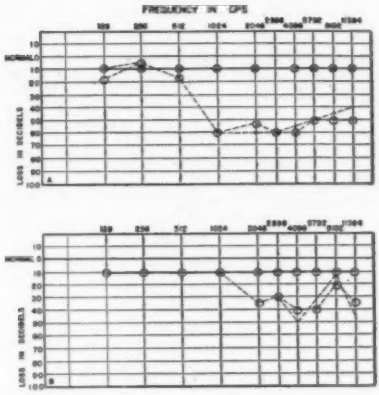

FIGURE 1. Audiograms of shipyard workers. Solid lines, hearing as tested before employment. Broken lines, A, hearing recorded after seven hours of work in the chipping school; B, hearing recorded after one month of work in the chipping school. From McCoy (*137*), with permission of the author and the American Medical Association, Chicago, Illinois.

does, apparently, find that initially the workers are more bothered by the noise than after working in it for several weeks. This is similar to an observation by Larsen (*128*) that initially workers experience a buzzing and ringing in their ears which vanishes after several days of work in a noisy factory.

It might now be asked whether or not the measured residual hearing losses are permanent, or a defect that disappears with rest. Pertinent to this is a study by Chamberlain (*27*), who found great individual differences among boilermakers in this regard. Figure 2 shows the recovery experienced after a 15-hour rest and a six-months rest. Boemer (*11*) states that recovery can continue for as long as two months.

Davis, Morgan, Hawkins, Galambos and Smith (*47*) in a laboratory experiment on stimulation deafness found recovery from sound exposure extending for several weeks. In these studies, however, the exposures were brief and widely separated and not of the daily type encountered in the industrial situation. In all probability the amount of recovery afforded the deafened worker by a more than 10- to 20-hour respite from noise is of only academic, though perhaps medical interest in that the worker is daily re-exposed to the noise usually after a rest period of about that length.

It could be argued that the deafness accrued by the industrial worker is a beneficial adaptation that shields him from 'buzzing' ears and the like. This seems unlikely, however, in view of the severity of deafness encountered and the findings of certain laboratory experiments that real damage can be inflicted upon the cochlea of animals by intense noise stimulation. Also, not to be forgotten is the fact that only a certain percentage of workers become afflicted with deafness even though exposed to the same intensities of noise. If this deafness was merely an 'adaptive' reaction not involving damage it could be expected to occur for all persons.

Type of Injury. Although post-mortem evidence of damage to the ear as a result of industrial noise is lacking for human subjects, otological examination definitely places the damage in the inner ear or eighth nerve.[1] This is, of course, in accordance with

[1]Habermann (*86*) made post-mortem examination of several boilermakers with histories of deafness and found cochlear degeneration. The men were extremely old, however, and since cochlear degeneration is fairly common in older people, his findings do not demonstrate that the cause of the degeneration was noise stimulation.

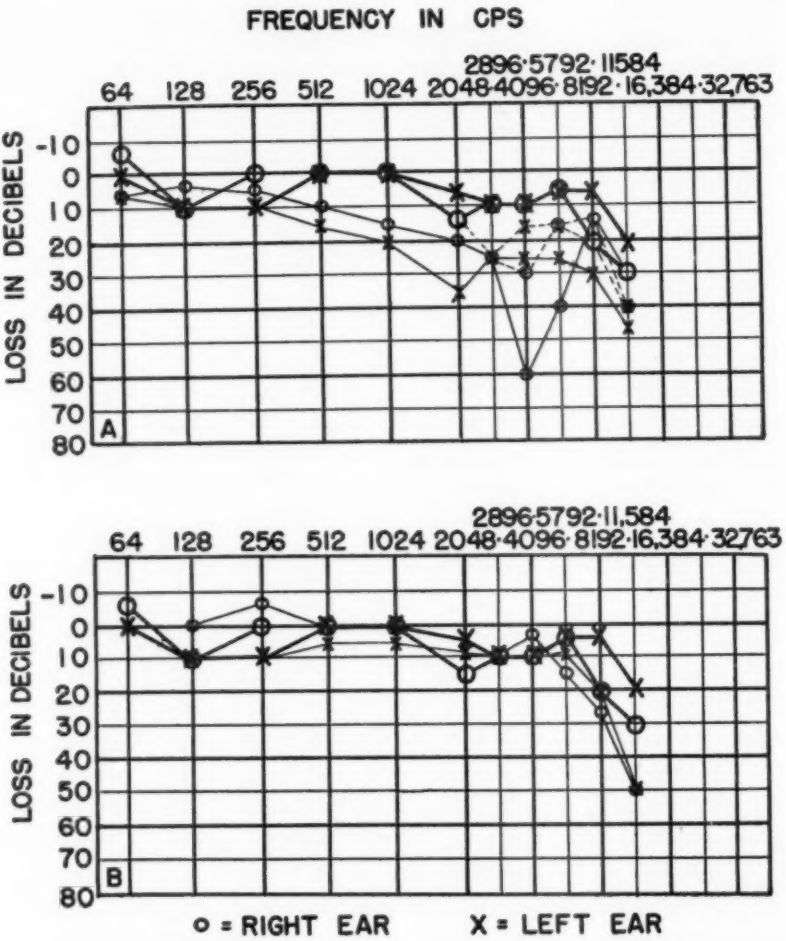

FIGURE 2. Audiograms of boilermakers. Heavy lines, hearing recorded before the day's work. A, light lines, hearing recorded after 40 minutes bucking rivets inside the boiler; broken lines, hearing after 15 hours of subsequent rest. B, light lines, hearing six months later with no exposure to similar excessive noise in the interim. From Chamberlain (27), with permission of the author and the American Medical Association, Chicago, Illinois.

the laboratory studies with animals, which have been reviewed by Kemp (*108*).

Sacher (*202*) according to Larsen (*128*) found, for example, that of 458 boilermarkers 73.4% possessed some degree of deafness; of these 82.7% suffered cochlear malfunction while only 17.3% had middle ear infections. In most of the studies of professional

deafness ample precautions were taken to eliminate from consideration those persons suffering from ear infections or with previous histories of infections.

Effects of Age. Early investigators felt that the increasing incidence of deafness with years on the job proved that repeated exposures over the years progressively increased the degree of deafness. As has been long recognized, deafness increases in the general population with age, presumably independently of exposure to noise although it has been suggested by Bunch (*14*) that the sounds of daily living account for this deterioration. Whatever the facts, the publication of hearing norms for the population attending the 1939 World Fairs at New York and San Francisco, as measured by Bell Telephone Laboratories (*226*), permitted comparisons between 'normals' and industrial workers for comparable age groups.

Figure 3 is from such a comparative study made by Gardner (*68*). Figure 3A is for the normal World's Fair population and Figure 3B is for shipyard workers. Considering the differences in auditory acuity for the normals between the B and E age groups, there is about a 10-db decrease in hearing with a 20-year increase in age; the difference between the matched groups, B and E, for the shipyard workers is likewise about 10 db (the A groups do not seem to be closely enough matched in age to include in the comparison). This would seem to indicate that the greater degree of deafness among the older employees was due to increased age rather than repeated exposures to the noise. Apparently after an initial loss, perhaps stabilized after a month's exposure

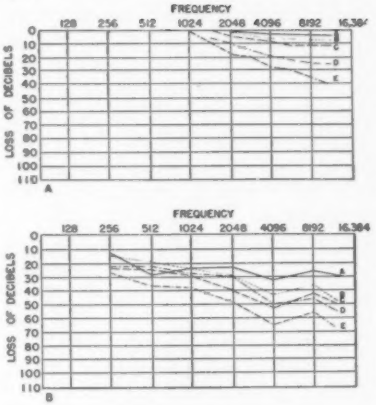

FIGURE 3. Comparison of auditory acuity of normal population with that of shipyard workers. Top, World's Fair population: A, 10-19 years; B, 20-29 years; C, 30-39 years; D, 40-49 years; E, 50-59 years. Bottom, 296 shipyard workers: A, 16-20 years (N=28); B, 21-30 years (N=92); C, 31-40 years (N=120); D, 41-50 years (N=44); E, 51-65 years (N=12). From Gardner (*68*), with permission of the author and the publishers of *Industrial Medicine.*

(McCoy, *137*) further losses in hearing of the worker is due primarily to increasing age rather than repeated exposure. A similar conclusion can be reached from an examination of data reported by Rosenblith (*190*).

Possible Error in Comparative Studies. It is to be noted that the use of the electronic audiometer from the 1930's on has enabled the investigators to measure more precisely hearing losses at various frequencies of sound and to establish norms. In most of the studies reported the hearing losses were taken as the difference between the threshold intensities required for the subjects under study and the average threshold intensities required for an entirely different population tested in a *properly sound insulated room* at the 1939 World Fairs. It has been

found that even in the testing rooms of some otologists there is enough residual noise to elevate the thresholds of the average normal person by 10 db or more (*100*), and the testing conditions present in many of the experiments conducted in industry must have left much to be desired. This means that it would not be amiss to judge that the degree of deafness measured in some of the investigations reported were overestimated, to be conservative, by 10-15 db. This uncontrolled factor would, of course, cause no appreciable error in cases of severe hearing losses, but may represent an appreciable error in the determinations of mild losses (less than 15 db).

Structure of the Cochlea and Deafness. Almost without exception, hearing losses due to noise among industrial workers appear in the high frequency range (above 1000-2000 cps) and only after prolonged exposure (or age) do the losses extend into the lower frequencies. The prevalence of a hearing defect above 4000 cps or of a 'dip' around 4000 cps has lead to much speculation concerning the cause. It has been held, as reviewed by Larsen (*129*), for example, that the portion of the cochlea, which according to the place theory of sound perception transduces sounds of 4000 cps into neural impulses, is weakened because of a bifurcation of blood vessels and a constriction within the cochlear structure at that point. The condition supposedly makes that portion of the cochlea vulnerable to various toxic conditions, head injury, disease and noise that precede or acompany a hearing loss at 4000 cps. Recent anatomical studies (*255*), however, cast doubt on the contention that the cochlea is structurally anomalous in the region (4000 cps) as originally suspected.

Relationship between Sound Spectrum and Hearing Loss. While it is incontestable that hearing losses around 4000 cps are found among industrial workers (and frequently in the 'normal' population) without ear infections, it is possible that rather than the cause being a structural weakness of a particular portion of the cochlea, this locus of deafness is predictable from a general principle relating auditory acuity and the spectrum of sound stimulation.

Underlying this theory are the results of stimulation deafness experiments carried out under laboratory conditions on various forms of animals, including man. It is not the purpose of this report to review the literature on stimulation deafness but a recent series of experiments conducted by Davis, Morgan, Hawkins, Galambos and Smith (*47*) that represent the most exhaustive studies done to date on man will be described briefly for the light they cast upon the general problem of the pattern of hearing losses resulting from exposure to noise.

The audiograms in Figure 4 were made at various times following exposure to pure tones of different intensity and duration. The exposures, while a little more intense than the 'noise' levels to be found in a noisy factory, were relatively brief. In addition to the rather rapid recovery from hearing loss, it should be noted that the hearing loss appears to be centered about one-half octave above the frequency of tonal stimulation. Perlman (*168*) found that with test tones of 512, 1024, 2048 and 4096 cps the greatest loss lay about one octave above the stimulus tones, and Rüedi and Furrer (*197*) demonstrated that

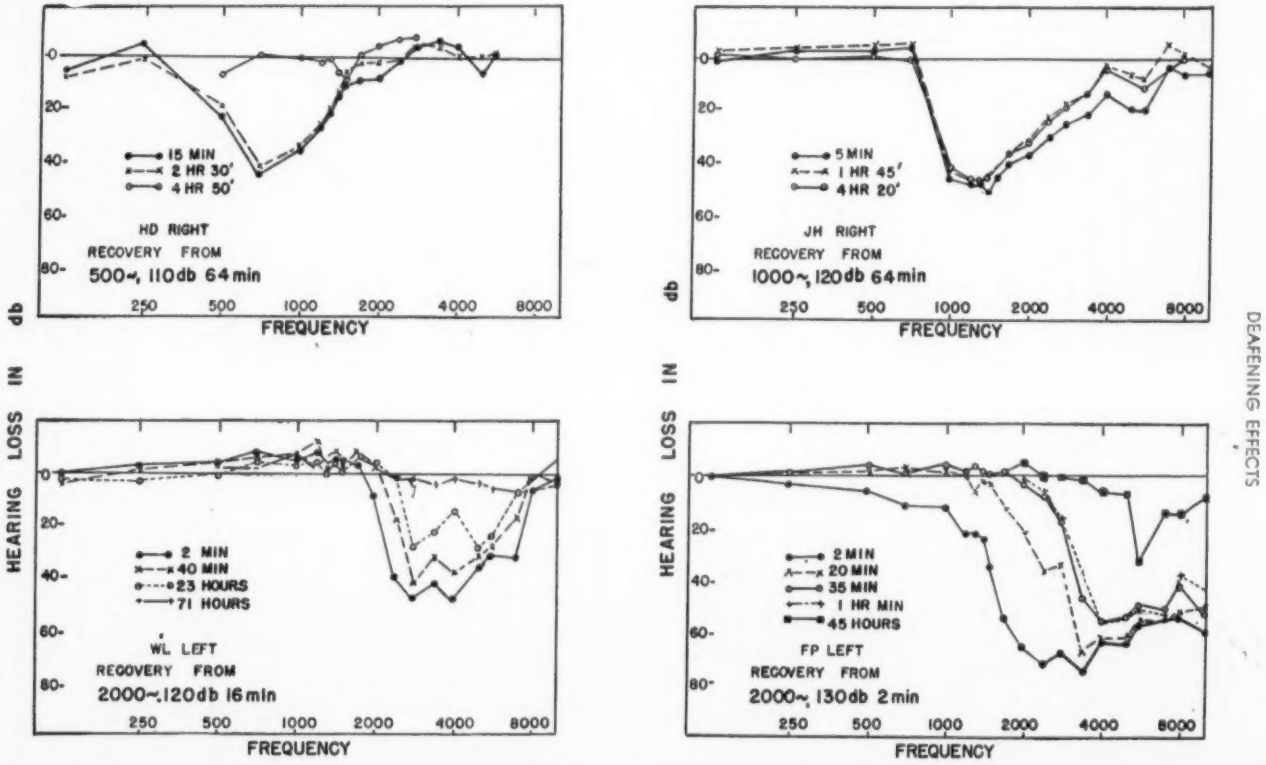

FIGURE 4. Audiograms following exposures to various pure tones and durations as indicated. From Davis, et al. (47).

with pure tone stimulation hearing loss begins just below the excitation frequency and reaches its maximum about one octave higher.

Other findings of Davis, Morgan, Hawkins, Galambos and Smith presented in Figure 5A show the average hearing loss incurred by a band of

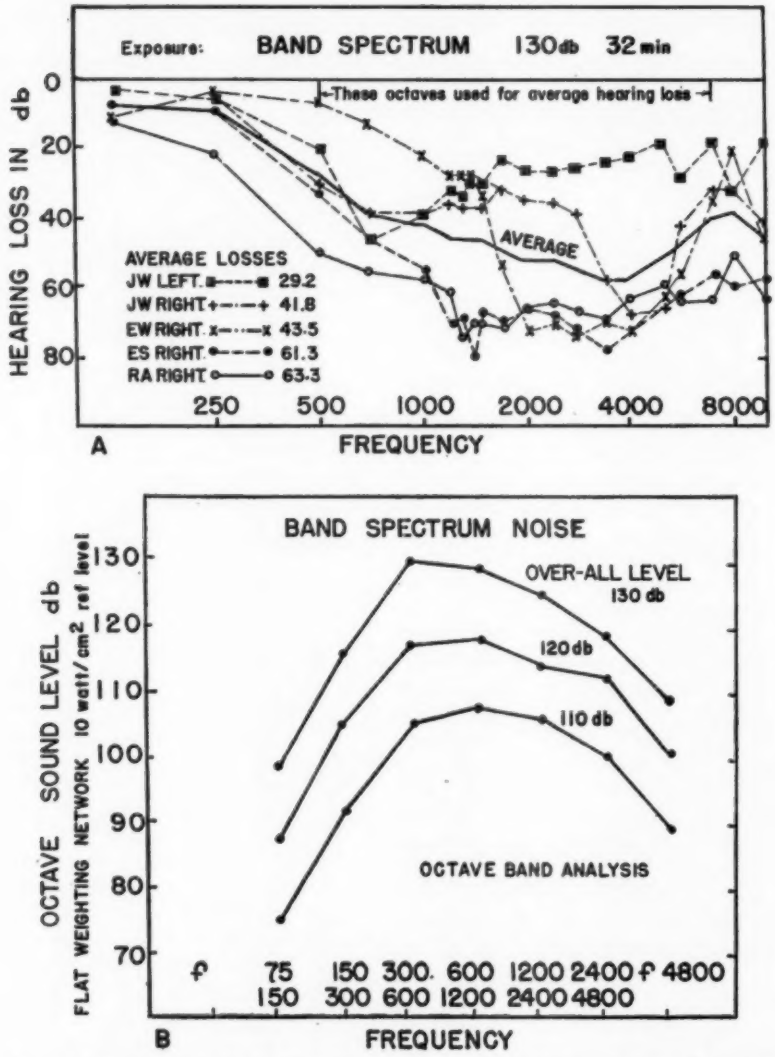

FIGURE 5. A, audiograms for 5 subjects following 32-minute exposure to band spectrum noise shown in B. From Davis, et al. (47).

noise with the spectrum shown in Figure 5B. It is seen that the average audiogram after exposure roughly approximates the noise spectra turned upside down and that the hearing defects, though shifted somewhat to the higher frequencies, are roughly proportional to the intensities of the frequency components of the noise.

Since the ear is most sensitive at about 2000 cps one would expect, with exposure to an intense noise that contained all audio frequencies at about equal intensities, that the greatest hearing loss would occur in the 2000-4000 cps region.

Figures 23 and 24, given in Part III of this report, and Figures 6 and 7 below indicate that for a wide variety of industries the noise is greatest in the middle and upper frequencies. This could account, in accordance with the findings of Davis et al, Perlman, and Rüedi and Furrer, for the pattern of audiograms discovered among industrial workers without recourse to the suspect notion of an inherent weakness of a portion of the cochlea. Instead it may be supposed that hearing losses below 1000 cps do not occur in professional deafness be-

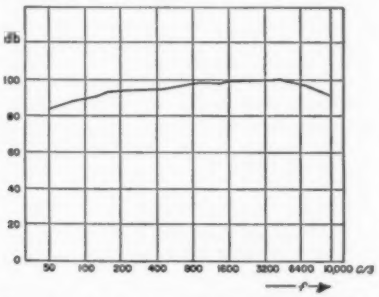

FIGURE 6. Noise spectrogram of a mechanical weaving mill. From Rüedi and Furrer (*197*), with permission of the author and the Acoustical Society of America, Washington, D.C.

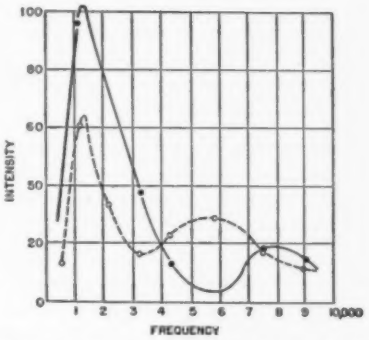

FIGURE 7. Spectrum of the noise produced by riveting (after Perwitzschky and Lanzig). From Larsen (*129*), with permission of the author.

cause of the lack in industrial noises of frequency components in that region that are intense relative to the sensitiveness of the ear (See Figure 8).

Hydrodynamic Action and Deafness. Rüedi and Furrer (*197*) suggest that the 4000-cps dip so common to audiograms may be related to the hydrodynamic action of the fluid in the cochlea. Békésy (*246*) has shown that eddies are formed in the lymph fluid of the cochlea when the ear is stimulated with sound. Rüedi and Furrer propose that when the ear is stimulated simultaneously with sound frequencies above and below 4000 cps, a strong, mechanical pull due to eddies rotating in opposite directions is placed on the portion of the cochlea where the 4000-cps tonal stimulation is localized and thereby causes a 4000-cps deafness. Further experimentation, however, is required before it can be stated that this hydrodynamic action is the primary or even one of perhaps several causes of localized hearing losses.

Intensity Levels. Parrack, Eldredge and Koster (*161*) have conducted a

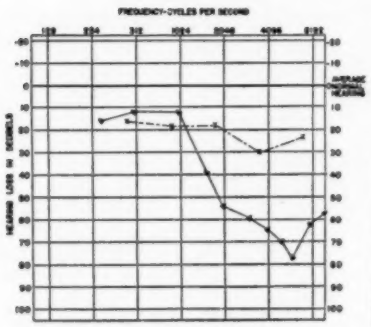

FIGURE 8. Comparison of 'normal' and industrial hearing loss in middle age. Broken line, average loss age 40-49, World's Fair population; solid line, average loss for boilermakers (average age about 45) after 15 years' service. Zero line, minimum audible pressure threshold. From Rosenblith (*190*) with permission of the author and the Acoustical Society of America, Washington, D. C.

series of experiments using a turbojet engine and a special siren for generating sounds of over 150 db re .0002 dyne/cm². It was found that for exposure of three to ten minutes severe hearing losses (60 db) occurred but that hearing returned to normal after 1-7 days rest. Whereas sounds of this intensity, having over 2000 times the power of common machine noises, are not representative of industry, the experiments demonstrate the amazing resistance of the ear to permanent damage.

While it has been demonstrated that both temporary and perhaps permanent deafness result from exposure to noises occurring in industry and to some extent probably in everyday life, it is not clear just what intensities are required to effect damage. There is some question as to whether or not the hearing losses reported for industrial workers in the various studies are not somewhat exaggerated due to inadequate testing conditions, lack of measures before exposure, and of proper evaluation of recovery. In addition, there are great individual differences in susceptibility.

Maximum Safe Intensity Level. Sleight and Tiffin (*222*), in a recent review article, list a number of investigators who make estimates ranging from 80 to 100 db as being maximum levels of noise to which a worker may be subjected without incurring deafness. In many industrial situations noise levels equal or exceed these levels as evidenced by the spectra given in various figures and in Table 1, taken from Sabine and Wilson (*201*).

A fair, perhaps conservative, evaluation of the laboratory and industrial studies on stimulation deafness would seem to be that for long and intermittent exposures any frequency of sound (or narrow band not exceeding the critical width) that is 85 db or less above .0002 dyne/cm² will not cause any temporary or permanent deafness.

TABLE 1. Noise levels of various machines at a distance of 3 feet. [From Sabine and Wilson (*201*).]

Machine	*Decibels*
Punch presses, various types	96-103
Headers	101-105
Drop hammers	99-101
Bumping hammers	100
Hydraulic press	130
Automatic riveters	95-99
Lathes (average)	80
Automatic screw machines	93-100
Airplane propeller grinding	100-105
Cotton spinning	84-87
Looms	94-101
Sewing machines	93-96
Wood planers	98-110
Wood saw	100
Wire rope, stranding machines	100-104
Ball mill	99

The 'guess' that tones 85 db above .0002 dyne/cm² may cause some deafness, either temporary or permanent, applies only for long periods of exposure, applied intermittently over months or years. On the other hand, for brief exposures lasting up to an hour, the intensities necessary to cause deafness appear to be in the order of 100 db re .0002 dyne/cm² for any frequency or critical band.

Critical Band Concept and Stimulation Deafness. It has been assumed by Fletcher and others that the concept of critical bands (the narrowest band around any frequency which just masks that frequency when of equal over-all intensity) should cover not only masking phenomena as described in Part III of this report but also the deafening effect of noise. The assumption is that since the addition of sound frequencies beyond the critical bands does not contribute to the masking effectiveness of the noise within the critical band, these additional frequencies likewise contribute nothing to the deafening effect of the noise within the critical band.

It is possible, but undemonstrable with present data, that the degree of deafness could be predicted by the use of critical band measures of noise intensity and plotting such measures relative to 85 db above the threshold for pure tones in a manner somewhat similar to that described in Part III of this report for calculating speech intelligibility. A suitable threshold line would be that for minimum audible pressure which is presented as curve A in Figure 7 of Part III.[2] Because of the greater intensities required to reach threshold at low and at high frequencies, .0002 dyne/cm² would represent a more conservative, safer reference point for calculating the probable deafening effects of noise than the minimum audible threshold; further experiments are needed to determine which reference level is more suitable.

Over-all Noise Level Measurement vs. Spectrum Analyses. Because noise level meters as commonly used add together the pressures present in a noise throughout the range of sound frequencies, the over-all measures of noise level do not necessarily indicate their deafening effects. For example, a noise containing all frequencies at approximately equal intensity would measure more than 30 db higher than any single frequency component or even any 'critical band' of the noise. If the energy in a noise were mostly in the low and/or high frequencies, the over-all intensity level would be even less indicative of its potential deafening effects.

It is clear that *the spectrum of a noise must be analyzed before its deafening value can be estimated.* Unfortunately, most sound level measures in the past, for example those given in Table 1, are over-all measures of intensity.

Relationship of Hearing Loss to Social Adequacy

Partial deafness is recognized as a hardship, even though it does afford

[2]The minimum audible pressure threshold referred to is not to be confused with the normal hearing threshold. The latter is the mean threshold of hearing for persons of all ages as measured by the Bell Telephone Laboratories at the 1939 World's Fair and by the Public Health Service (*34*). This average threshold for the population is on the average about 15 db above the minimum audible pressure required to reach threshold on the most acute ears. It is represented by curve C in Figure 7, Part III.

some insulation against obnoxious sounds and noises. Nevertheless, the interpretation of the audiogram in terms of the handicap it places on a person in daily living is a medico-legal problem that is as yet not completely solved.

Amazingly enough, the damage wrought to hearing in industry, presumably by the exposure to noise, has apparently not been resented to a great extent by the individual workers, although in recent years legislation providing for compensation for occupational deafness has been enacted in Bulgaria, Czechoslovakia, Denmark, France, Germany, Danzig and USSR (*130*), and public health authorities elsewhere consider it a real menace.

Audiometric Method of AMA. In 1942 the Council on Physical Medicine of the American Medical Association published a tentative standard procedure for evaluating the effective hearing loss in medico-legal cases. The recommendations were revised in some details in 1947 (*33*). The procedure is based on the well-established method of measuring hearing loss with a pure tone audiometer at octave frequencies. The audiometers used are calibrated so that hearing defects are measured in decibels with respect to the intensities required to be just detectable for the average person in a quiet room.

The procedure suggested by the American Medical Association does two things:

1. It recommends that thresholds for only four frequencies, 512, 1024, 2048 and 4096 cps, be considered in the calculation of hearing losses since most speech sounds fall within this range. It is assumed that the most important function of hearing for the average person is the hearing of speech.

2. The method further assigns different weights to these four frequencies, as is shown in Table 2. The column of numbers under each frequency in this table represents the percentage hearing loss that should be attached to the degrees of audiometric hearing loss indicated in the left hand column.

TABLE 2. Tentative standard procedure for evaluating the percentage loss of hearing in medicolegal cases (*33*).

Hearing Loss in db	*Frequency in cps*			
	512	*1024*	*2048*	*4096*
10	.2	.3	.4	.1
15	.5	.9	1.3	.3
20	1.1	2.1	2.9	.9
25	1.8	3.6	4.9	1.7
30	2.6	5.4	7.3	2.7
35	3.7	7.7	9.8	3.8
40	4.9	10.2	12.9	5.0
45	6.3	13.0	17.3	6.4
50	7.9	15.7	22.4	8.0
55	9.6	19.0	25.7	9.7
60	11.3	21.5	28.0	11.2
65	12.8	23.5	30.2	12.5
70	13.8	25.5	32.2	13.5
75	14.6	27.2	34.0	14.2
80	14.8	28.8	35.8	14.6
85	14.9	29.8	37.5	14.8
90	15.0	29.9	39.2	14.9
95		30.0	40.0	15.0

Although the proposed method does not suggest that the age factor should be considered in the calculation of percentage hearing loss in cases of industrial deafness, an adjustment to eliminate the amount of deafness due to normal deterioration would seem logical.

Curve C of Figure 3B represents an example of industrial deafness for a fairly large sample ($N = 120$), and since Gardner gives the average age

(31-40 yrs) of his subjects, the percentage hearing loss is calculated by (1) measuring the hearing loss of the workers relative to the standards for normal young adults and determining the appropriate percentage from Table 2, (2) finding the percentage hearing loss of normal adults 30-39 years old, and (3) subtracting the percentage obtained in step 2 from that of step 1.

Accordingly (see Table 3) a .1 percentage hearing loss represents the average handicap incurred by the average person 30-39 years old; a further 28 per cent loss is suffered by the subjects in this particular example because, presumably, of their exposure to noise.

Actually, the percentage losses due to noise are overestimated in these calculations inasmuch as the procedure recommended by the Council on Physical Medicine weights the hearing in the poorer ear 1/7th as much as the losses in the better ear. The formula is: $\textit{binaural hearing} = \frac{\textit{avg. better ear losses} \times 7 + \textit{avg. poorer ear.}}{8}$

The audiograms in Figure 3B, which were used for these calculations, represent an average of the losses in both ears equally weighted. The individual ear audiograms were not reported in the study used as an example.

For the particular age group examined, the deficit due to age alone is negligible; however, the deficit increases with age so that the hearing of average 50-59-year-old normal persons is about 5.6% below that of the average person.

Speech Articulation Method. Davis (*43*) has developed a more direct measure of ability to hear speech. In this method a number of specially prepared and recorded word tests are administered to the listener at different intensity levels ranging from what seems faint to loud for the person with normal hearing. The percentage of words heard correctly at three standard levels of intensity is averaged and taken as the 'social adequacy index' for the hearing of that person. In Figure 9 are shown the 'articulation' curves (the percentage of words heard correctly) for normal hearing and for two cases of impaired hearing. The Social Adequacy Index for hearing (SAI) is the average of the articulation scores achieved for the three standard intensities, 55, 70 and 85 db re .0002 dyne/cm². In practice only two tests are administered. One is a test of the patient's threshold for

TABLE 3. Example of use of tentative standard procedure for evaluating the percentage loss of hearing. [Data taken from Gardner (*68*), as presented in Fig. 3.]

	Hearing Loss in Decibels		*Percentage Hearing Loss**	
Frequency	*Normal 30-39-yr.-old people*	*31-40-yr.-old workers*	*Normal 30-39-yr.-old people*	*31-40-yr.-old workers*
512	0	25	0	1.8
1024	0	30	0	5.4
2048	5	40	0	12.9
4096	10	50	.1	8.0

*Percentage loss due to age and noise, 28.1; to age, 0.1; to noise, 28.0.

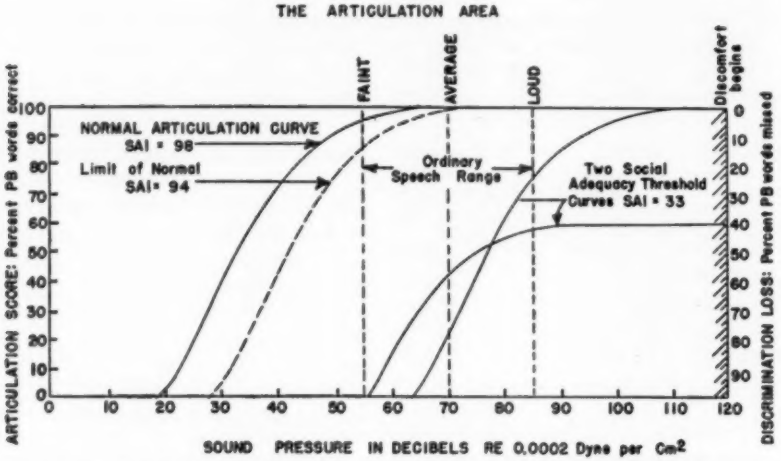

FIGURE 9. Social Adequacy Threshold Curves (based on average percentage of PB words correctly understood at three speech levels, 55, 70 and 85 db) for normal hearing and for two cases of impaired hearing. From Davis (*43*), with permission of the author and the publishers of *The Laryngoscope*.

speech. This serves to locate the 'foot' of his articulation curve. The second test is a discrimination test. One of the standardized lists of monosyllabic words is given at a level at least 35 db above the patient's threshold for speech. The articulation score on this test gives the height of the plateau of the patient's articulation curve. It is assumed that the shape of the curve is normal; and therefore two points are enough to locate it on a chart like Figure 9. The articulation scores corresponding to speech levels of 55, 70 and 85 db re .0002 dyne/cm² can then be read off and averaged. In practice a table is employed in which the SAI corresponding to all combinations of threshold for speech and 'discrimination loss' have been calculated in advance.

Although the SAI method requires instruments not available to the average otologist, the results are more directly interpretable in terms of the effects of deafness upon the lives of the patient than the pure tone audiograms, inasmuch as this latter method has not been validated against speech tests. The relationship between the two methods is under further investigation at the Central Institute for the Deaf (*221*).

Besides face validity, the SAI method has a characteristic not present in the audiometric method that should be mentioned. That is the fact that it reflects loss in ability of the patient to discriminate normally among sounds that lie above his threshold. With this condition, a person hears the sound but cannot understand what is said. The words sound mangled and jumbled. This phenomenon, which presumably occurs only for nerve type deafness (as could be caused by overexposure to noise), is not directly measured by audiometric threshold determinations. A case of this type is

shown by the curve in Figure 9 that does not rise above 60 per cent word articulation and having an SAI of 33. An SAI of 33 is considered by Silverman, Thurlow, Walsh and Davis (*221*) as the threshold of social adequacy.

The Use of Earplugs

It was suggested earlier in this report that if noise cannot be eliminated or abated, its deleterious effects can be somewhat prevented by the use of ear plugs.

Two main varieties have been developed and used, the plug type that fits snugly into the external meatus of the ear, and a cushion type held by a head band or in a helmet that lies around and over the ear. Among the plugs, there are many varieties: dry cotton and wool, wet or wax-impregnated cotton or wool, wax, plastic and rubber.

The crucial test of the adequacy of an earplug is, of course, how much it attenuates sound passing through the external ear canal. This can be determined by measuring the threshold shift that occurs when the ear is plugged. This shift at a number of frequencies for a number of different kinds of plugs is shown in Figure 10.

In spite of the utmost care in design and selection of materials, however, some people find standard sizes of earplugs uncomfortable, at least upon initial use. Other complaints have been that they are easy to lose and hard to keep clean. In addition, after considerable exposure to intense noise and the onset of deafness, the noise becomes less disturbing to the worker

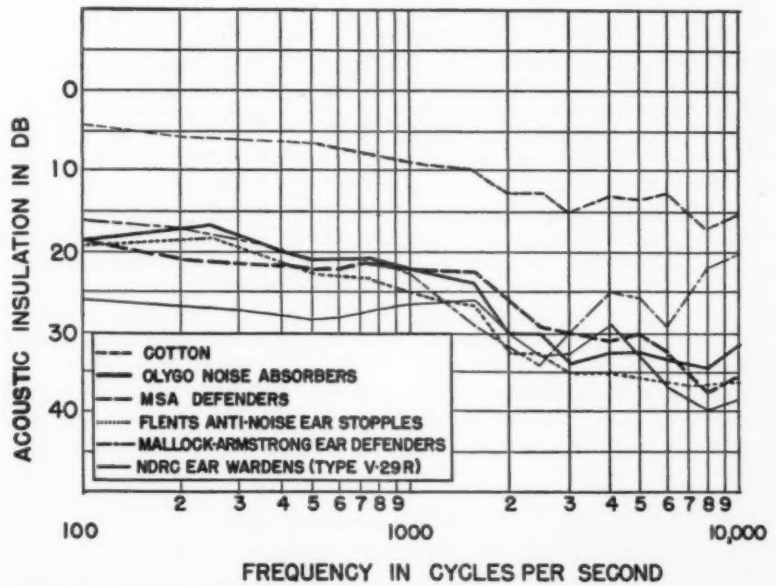

Figure 10. Attenuation in db for pure tones afforded by various types of earplugs. From Miller, Wiener and Stevens (Part III, *130*).

so that, to him, the earplugs do not seem so necessary. The hygienic aspect of wearing earplugs has been examined by Davis (*42*) and found to be much less a hazard than the possible deafness without them.

It is possible that a certain degree of the discomfort could be overcome, although at much greater expense, by the use of cushion fittings over the ears. Also, when earplugs are molded individually for each person it is found that the plugs are reasonably comfortable and provide good sound attenuation (*35, 104*).

Effects of Earplugs on Speech Reception. The development and use of earplugs and 'ear covers' has had a rather interesting history. The use of such devices was probably inhibited, at least in the armed forces of the USA, as the result of discussion centered around their function during World War I (*82*). It was feared that soldiers and sailors would fail to hear faint signals and commands when wearing earplugs. There were attempts to build earplugs that would let 'little sounds' through but keep out 'big sounds.'

The effect of wearing earplugs on the intelligibility of speech has been tested experimentally and results are presented in Figure 27 in Part III of this report. In any noise whose effective masking on speech is more than 60 db, earplugs will not interfere with speech reception.[3] By 'effective masking' is meant the number of db the noise elevates the threshold for speech. The effective masking is usually much less than the over-all intensity level of the noise measured relative to .0002 dyne/cm^2. It is the simplest measure that may legitimately be used for comparing the masking effectiveness of different types of noise.

In noises with effective masking of more than 60 db the wearing of ear plugs actually *improves* the reception of speech. While it seems illogical that plugging the ears should permit one to detect sounds as well or better than with the ears open, the phenomenon is easy to explain. For one thing, the insertion of ear plugs reduces the noise reaching the ear as much as it reduces the speech signal. Therefore, the signal-to-noise ratio remains constant. The over-all reduction of the noise and the speech levels presents a more moderate intensity of sound to the middle ear with a concomitant reduction of distortion. The situation is perhaps analogous to the improvement of vision when the glare of extremely bright light is reduced.

It has been argued that the insertion of ear plugs would reduce speech sounds that were only slightly above the absolute threshold of hearing to a completely inaudible level. Speech sounds of such weak intensity would not be heard in any case, however, due to the masking effect of noise. Therefore, the attenuation afforded by the ear plugs would again have no effect on the intelligibility of speech as long as the noise produces an effective masking of 60 db. It is to be noted, however, that it is the effective masking for speech (or any other signal) of the noise that is the determining factor as to whether the wearing of earplugs will interfere with hearing and not the over-all noise level as measured by a sound level meter.

[3]It might be added that a hearing loss resulting from an explosion or the firing of a gun may temporarily deafen the listener so that his effective hearing in the quiet (between gun firings) will be no better than the hearing of a person who is wearing ear plugs but who, as a result, is not suffering from temporary deafness.

Deafness in the Military Situation

Deafness may be incurred during military service. The situation, however, is much more complicated than the mere presence of noise, so that sharp distinctions must be made among: (1) the effects of noise or sound, (2) the effects of blast or shock waves, and (3) the effects of changes in barometric pressure.

Shilling (*217*) and Shilling and Everly (*218*), for example, attribute hearing deficiencies among submarine personnel as being due in part to the compound effects of noise, gun blasts and barometric pressure changes.

Shock Waves. The effects on deafness of military noises such as is present in tanks, engine rooms of boats, and airplanes are no different from the effects described previously for the industrial situation. Shock waves, however, represent a different order of insult to the ears. A blast or 'shock wave is to a sound wave what a tidal wave is to a ripple' (*127*). The change in pressure in a sound wave is small compared to the normal undisturbed air pressure, whereas the pressure increase in a shock wave may be greater than the total original atmospheric pressure. Shock waves are single waves and must be considered as successive transient phenomena, not as steady states like a sustained tone with a particular frequency.

Although shock waves occur frequently enough in everyday life, it is around guns, cannons and bombs that the effects reach an appreciable and measurable magnitude. The momentary peak pressures near the source of these explosions often far exceed atmospheric pressure. Thompson (*238*) gives a number of measures of intensity for shock waves from different sources. Often these transient sound pressures of shock waves are measured in terms of pounds per square inch rather than dynes per square centimeter.

Effect of Shock Waves on Deafness. There will be found over threescore articles in the bibliography that are concerned with the effects of blasts, particularly gun blasts, upon hearing. Typical results for exposure to gun and cannon fire are given in Figure 11 taken from Machle (*140*). Machle experimentally exposed gunnery instructors to 37 and 75mm and 30 caliber guns, obtaining audiograms before and at various stages after exposures. He also surveyed the hearing loss for a large number of gunnery instructors.

Some of Machle's findings can be summarized as follows:

(1) Gunnery instructors in general display about an 11% hearing deficiency according to the tentative AMA method of computation described previously.

(2) There was a regular but partial recovery following the termination of exposures.

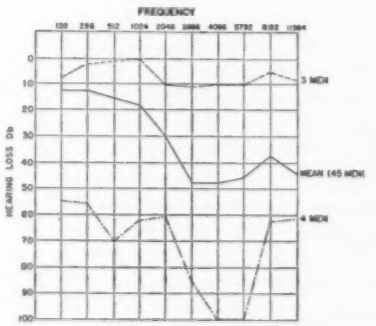

Figure 11. Mean and extreme audiograms of 45 gunnery instructors (ages 19-36; no significant histories of ear disease). 80% of the men used cotton earplugs; 20% used no earplugs. From Machle (*140*), with permission of the American Medical Association, Chicago, Illinois.

(3) With repeated exposures there was a cumulative hearing loss with retarded recovery, lasting up to eight days.

(4) Earplugs prevented the hearing loss.

Murray and Reid (*157*) measured temporary hearing losses ranging from 55 to 85 db due to pressures ranging from 1½ to 8 lbs. per square inch; whereas after the rapid firing of a rifle, ¼ lb. per square inch near the muzzle, for over 100 rounds they measured small hearing losses.

Damage to Eardrum. Besides suffering from temporary and apparently permanent deafness as the result of repeated exposures to gun and concussion blasts, military personnel may sustain ruptured eardrums. Glass (*72*) and others have found that the rupture of the eardrum by a blast wave does not necessarily lead to deafness. It is generally held (*85, 170*) that when the eardrum ruptures the more delicate inner ear mechanism is thereby protected.

Collins (*31*) examined a number of battle casualties and found that 20% sustained some aural trauma due to blast. Forty per cent of these cases showed some degree of deafness, but the majority of those with deafness had infected middle ears resulting from ruptured eardrums.

Protections against Blast. The use of earplugs for protection against gun blast has been almost universally recommended. The 20 to 30 db of protection afforded by proper plugs is sufficient to prevent rupture of the eardrum in the severest of blast waves usually encountered. The ear itself, in addition, appears to be admirably constructed to accept blast waves of 'reasonable' intensity.

Perlman (*170*) has investigated the reaction to blast of the ossicular chain of bones connecting the eardrum with the inner ear. He lists a number of characteristics of the conductive mechanism of the middle ear that afford protection from shock or blast, such as the ballistic characteristics of the ear which prevent it from following accurately the extremely rapid pressure changes of a blast wave and the manner of oscillation of the ossicular chain to intense sound and blast waves. Perlman demonstrated the effectiveness of a perforation in the eardrum in reducing blast transmission.

There is another mechanism in the ear that might be thought to protect the ear from blast—the middle ear muscles which can reduce the oscillation of the ossicular chain. The latent period of this reflex, however, around 10 milliseconds, is too long to protect against a pulse wave which may last but 1 millisecond (*172*).

Effects of Barometric Changes. The pressure change due to rapid changes in altitude or in barometric pressure is a very slow affair compared to sound or shock waves. The result is a changed steady-state pressure on the eardrum. Unfortunately, the air pressure on the inner side of the eardrum (in the middle ear) may not change as rapidly as the external pressure because the eustachian canal is not always open like the external ear canal. The result is a differential in pressure between the two sides of the eardrum.

There are numerous articles about deafness in flying and submarine personnel following rapid changes in altitude such as are encountered in diving an aircraft or in escape from a submarine. The effects of this rapid pressure change may involve bleeding in the outer and middle ear and, subsequently, an inflamed condition of the ear tissues with fluids forming in

the middle ear. Only rarely is the drum ruptured. These effects, however, are very painful.

It is not clear that any damage is inflicted upon the inner ear, except indirectly from possible infection in the middle ear. Hearing is affected, of course, by the presence of any fluids or exudates in the ear.

Inasmuch as flying and submarine personnel are usually exposed to fairly intense noise levels, deafness in these personnel may be due to the compounded effects of both noise and insults from barometric pressure changes. In commercial aircraft the noise levels and rates of ascent and descent are below the levels required for damaging the ear, and even for personnel in a military aircraft Campbell (*20*) states that deafness is not a significant problem.

General Conclusions

The study of the experimental literature on the effects of noise on the auditory mechanism reveals the following points:

(1) Exposure to intense noise from machinery causes partial and temporary hearing losses that persist for a few minutes to several hours. Apparently, continued repeated exposures over extended periods (years) may result in a partial but permanent deafness. The more intense the sound the greater the deafening effect. The maximum safe intensity at which no deafening effect will occur is probably in the neighborhood of 85 db above .0002 dyne/cm^2 for 'critical bands' of noise. The over-all intensity of a noise in decibels usually will not correctly indicate its deafening effect.

(2) Both field and laboratory tests indicate that deafness occurs for the dominant frequency in a noise and/or for higher frequencies.

(3) Exposure to gun fire and other shock or blast waves results in a partial deafness that lasts for a few minutes up to several days, and continued repeated exposure results in a partial but *permanent* deafness that may be progressive with continued exposure.

(4) Rupture of the eardrum may be caused by blast waves or by extreme and rapid pressure changes resulting from rapid changes in altitude such as may occur in military flying and submarine activity. Deafness resulting from such insult is apparently due to secondary effects occurring in the middle ear such as infection, the development of fluids and exudates, and the rearrangement of middle ear structures in addition to possible direct damage to the cochlear structure.

Earplugs which afford 20 to 30 db of sound attenuation for the middle range of frequencies will in practically all present industrial and military situations where noise and shock waves are a problem afford sufficient protection from the noise to prevent deafness. The wearing of proper earplugs in intense noise fields improves speech communication as well as giving comfort and protection.

Earplugs individually molded and fitted to each person would probably be the most comfortable and adequate method of protecting an individual from high levels of noise. There are certain earplugs now manufactured which provide good sound attenuation but not all people can wear them with comfort. Dry cotton, which has been used extensively by military personnel, does not afford much protection against the low and middle range of sound frequencies although it does reduce to some extent the intensity of high frequencies which subjectively are the most annoying.

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A&S—Deafness in submarine and aircraft personnel.
B —Literature concerned with blast or shock waves.
I —Industrial and clinical studies.
L —Laboratory experiments.
P —Studies involving earplugs.
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Part III EFFECTS OF NOISE ON COMMUNICATION BY SPEECH

THIS SECTION of the report is directed toward an understanding of the problem of communication by speech in the presence of the kind of noises encountered in the vicinity of power driven machinery, and under certain other special listening conditions.

To ascertain and measure the basic causes of failures in communication and the requirements for success, it is necessary to consider a number of rather complicated functions and relationships pertaining to the characteristics of speech, hearing and the intelligibility of speech sounds.[1] The most important of these factors are presented in the following paragraphs in as non-technical manner as possible. A brief discussion of these factors first should make the later presentation of the effects of noise on communication by speech more meaningful.

The Physical Characteristics of Speech

Spectra of human speech, as analyzed at the Bell Telephone Laboratories by Dunn and White (*20*), and at the Electro-Acoustic Laboratory, Harvard University, by Rudmose et al (*107*), are shown in Figures 1 and 2. For these determinations, the contributions of successive, narrow bands of frequencies throughout the audible sound region were averaged over periods considerably l o n g e r than the duration of a syllable. The results represent what is called the 'long average' spectrum of speech. M e t e r s with square law characteristics and suitable filters were used. The sentence, 'Joe took father's shoe bench out; she was waiting at my lawn,' which includes the m o s t important conversational speech sounds, was repeated over and over by talkers in the study conducted by Rudmose et al, whereas Dunn and White had their talkers read connected discourse. The variations in spectrum among s e v e n talkers are shown in Figure 2. For all of the men, the sound energy of speech extends from 100 cps to at least 8,000 cps.

Range of RMS Intensities Appearing in One-Eighth Second Intervals. Because of the dynamic nature of speech, the starting and stopping of sounds, the changes of pitch, etc., the intensity level of any narrow band of frequency varies widely from moment to moment. The distributions of frequency components, with respect to both instantaneous peak and root-mean-square (rms) intensity for intervals of one-eighth second (corres-

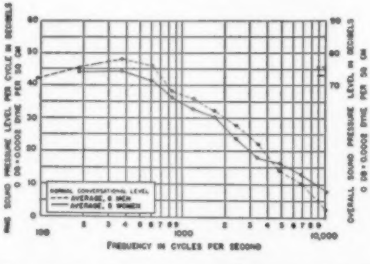

FIGURE 1. Average speech spectra at a distance of 30 cm from the talkers' lips. From Miller, Wiener and Stevens (*130*), after Dunn and White (*20*).

[1] It is beyond the scope of this paper to do more than indicate, at the proper places, the well-known techniques and instruments used in making the physical measurements of speech and noise. 'Articulation' or 'speech intelligibility' testing methods are less well-known. Briefly, a speaker reads person-to-person, or over a communication system, a list of standardized nonsense syllables, monosyllabic words, polysyllables or sentences to a listener or group of listeners who record what they hear. The answer sheets are then scored and the results expressed in percentage of items correctly recorded. For a detailed discussion of such methods, see *21, 45*.

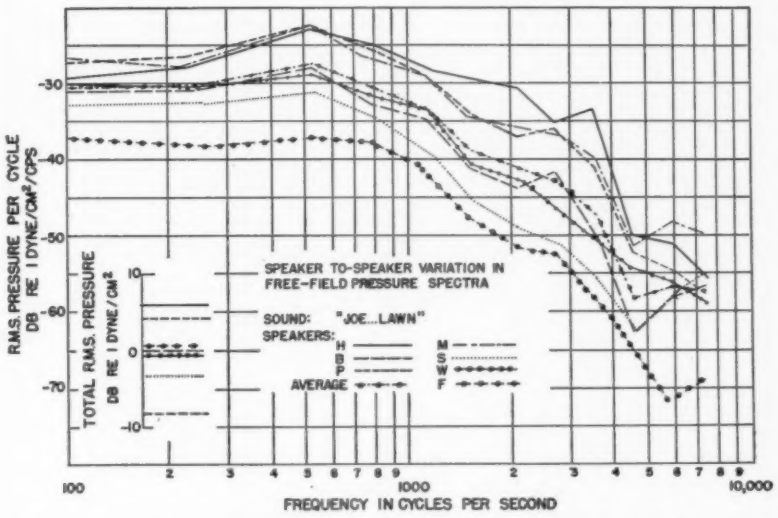

FIGURE 2. Person-to-person variation for sentence 'Joe . . . . . Lawn'. From Rudmose et al. (*108*), with permission of author and the Acoustical Society of America, Washington, D. C.

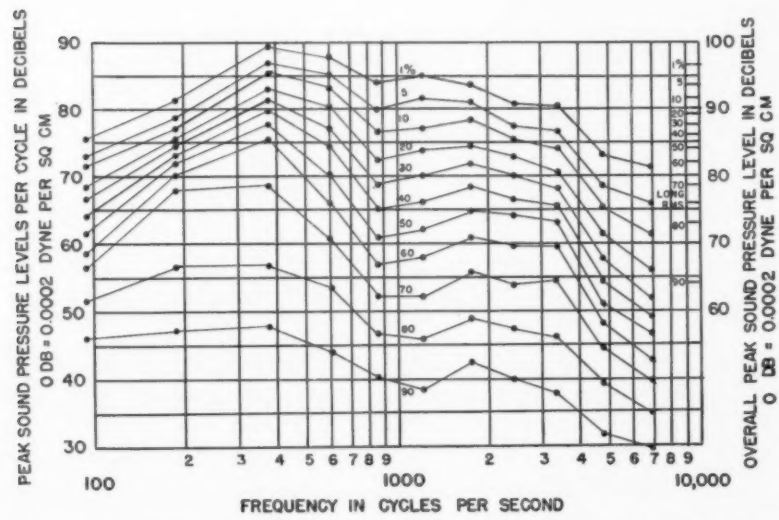

FIGURE 3. Peak pressure in ⅛-sec. intervals for conversational speech at a distance of 30 cm from the talkers' lips (Average of 6 men). From Miller, Wiener and Stevens (*130*), after Dunn and White (*20*).

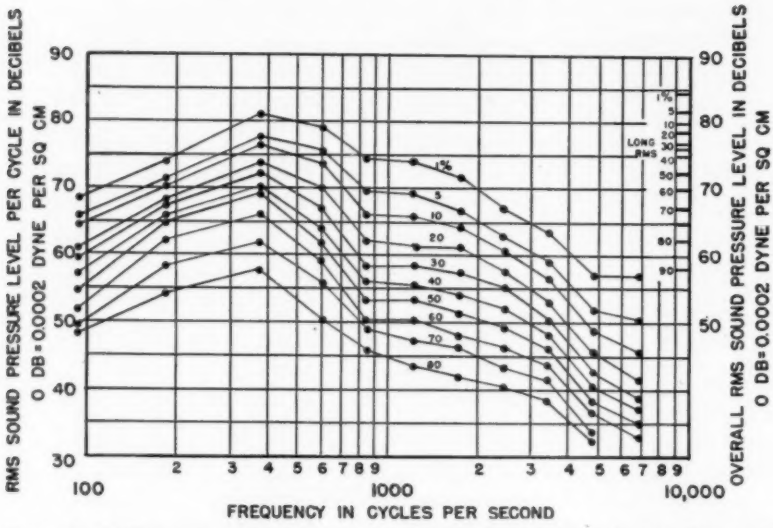

FIGURE 4. RMS pressures in ⅛-sec. intervals for conversational speech at a distance of 30 cm from the talkers' lips (Average of 6 men). From Miller, Wiener and Stevens (*130*), after Dunn and White (*20*).

ponding roughly to the duration of a syllable) have been determined by Dunn and White (*20*) and are shown in Figures 3 and 4. The percentages of one-eighth second intervals in which the sound pressure exceeded the value of the ordinate on the left are shown by the curves.

Note the ordinate and the markings on the right side of Figures 3 and 4. This ordinate gives the sound pressure level, summated over all frequencies, for ⅛ second intervals which occurred according to the percentages indicated. For example, Figure 4 shows that the rms sound pressure summated over all frequencies reached approximately 84 db re .0002 dyne/cm² 1% of the time, whereas for 50% of the ⅛ second intervals rms sound pressure reached about 72 db re .0002 dyne/cm².

Also, Figure 4 shows that the weakest value at each frequency falls approximately 30 db below the strongest value. This 30 db represents the dynamic intensity range from the weakest to the most intense sounds at each frequency. The listener must detect sounds throughout this dynamic range if he is to hear all the components in conversational speech. The dynamic range is over 42 db if peak pressures are considered, as in Figure 3, instead of rms values.

Difference between Instantaneous Peak and RMS Pressures. If the difference in decibels is taken between instantaneous peak and rms pressures for any given contour in Figures 3 and 4, the *instantaneous peak factor* for speech is obtained. This peak factor for the 10% contour is shown in Figure 5. The instantaneous peaks are 12 db higher on the average for all frequencies than the average rms value. It has not often been appreciated in the use of communication

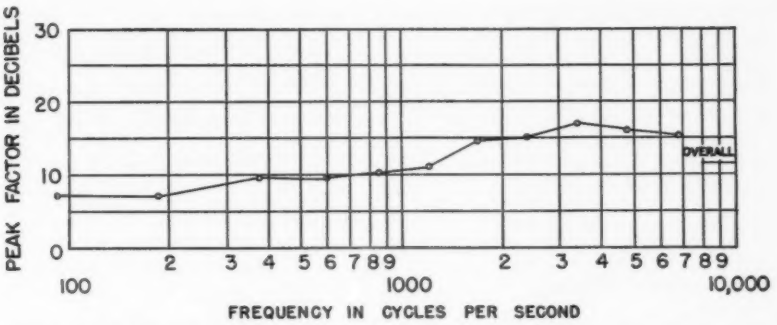

FIGURE 5. Peak factors of conversational speech at the 10% level of ⅛-sec. intervals. From Miller, Wiener and Stevens (*130*), after Dunn and White (*20*).

equipment that the peak factor of speech is so large and as a result, a 'chopping off' or 'amplitude distortion'[2] of the peaks of the speech waves has occurred because of inadequate power in the electronic amplifiers in military equipment and in many public address systems.

Vowel-to-Consonant Ratio. Another variation in the speech signal is important in the presence of noise and/or with non-linear amplification of the signal. This is the vowel-consonant ratio which, like the instantaneous peak factor, amounts on the average to about 12 db. The range between the weakest consonant [θ] and strongest vowel [ɔ] is of the order of 28 db (*109*). The vowel-consonant ratio is the difference between the average power of vowels and consonants. The oscillogram of the word *show* in Figure 6 exemplifies a difference in the intensities of a vowel and a consonant.

[2]In this paper 'amplitude distortion' and 'non-linear amplification' will mean that as the sound input to a system at a given frequency is increased in intensity above a certain level, the output from that system will not increase proportionately. The term 'frequency distortion' will mean that a system transduces or transmits different frequencies of sound with different gain.

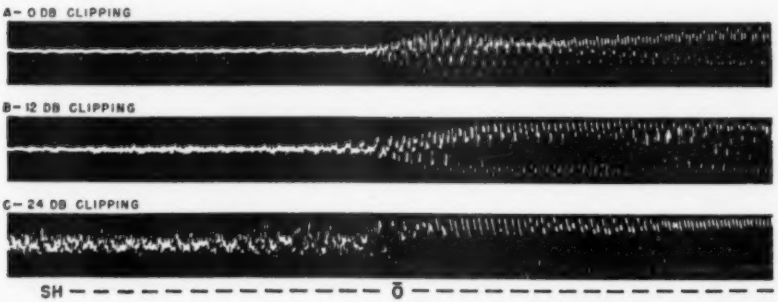

FIGURE 6. Oscillogram of the word *show*: A, No distortion; B, 12 db peak clipping and reamplification; C, 24 db peak clipping and reamplification. It is seen that the vowel-consonant ratio is reduced with peak clipping. After Kryter and Stein (*67*).

It is apparent from Figure 6 that the consonants are more likely to be masked by noise than vowels. On the other hand, non-linear amplification will distort the stronger vowel sounds first. The effects of these relationships on the intelligibility of speech will be presented later.

Some Characteristics of Hearing

Three fundamental characteristics of hearing are important for present purposes:

1. The ability to distinguish the presence of sound from the absence of sound. The minimum audible intensity of sound defines the *absolute threshold.*

2. The ability to distinguish the presence of a wanted sound (speech, music, tones, etc.) in a background of other sounds or noise. When the wanted sound is barely distinguishable from the noise, the ear is operating at the *masked threshold.*

3. The ability to respond to and discriminate changes in intensity up to at least 125 db above absolute threshold. Above this level other thresholds are reached and sound elicits, in turn, feelings of discomfort, tickle and pain. Above that level speech becomes less intelligible because, apparently, of its painfulness and/or an overloading of the ear.

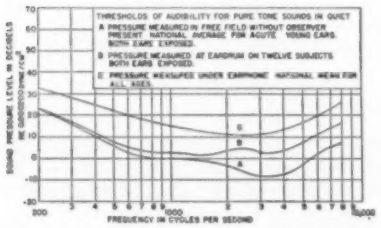
THRESHOLDS OF AUDIBILITY FOR PURE TONE SOUNDS IN QUIET
A PRESSURE MEASURED IN FREE FIELD WITHOUT OBSERVER PRESENT. NATIONAL AVERAGE FOR ACUTE YOUNG EARS. BOTH EARS EXPOSED.
B PRESSURE MEASURED AT EARDRUM ON TWELVE SUBJECTS BOTH EARS EXPOSED.
C PRESSURE MEASURED UNDER EARPHONE. NATIONAL MEAN FOR ALL AGES.
SOUND PRESSURE LEVEL IN DECIBELS RE 0.0002 DYNE/CM²
FREQUENCY IN CYCLES PER SECOND
200
1000
10,000

FIGURE 7. The audible threshold for pure tones with subjects in quiet. Curve A is based on data obtained by Sivian and White (*116*), B is Curve A corrected for the difference between pressure in the free field and at the eardrum as found by Wiener and Ross (*136*), and Curve C is the national mean for all ages (Part II, 227). From Beranek (*2*), with permission of the author and the Institute of Radio Engineers, New York City.

The Absolute Threshold. The absolute threshold for pure tones over the audible frequency range for normal young adults listening with both ears in a free field is shown in Curve A of Figure 7 (Taken from Sivian and White (*116*).) The tones were presented by a loudspeaker.

Wiener and Ross (*136*) measured the difference between free field pressure and pressure at the ear drum, and Curve B in Figure 7 represents the result of adding the appropriate corrections to Curve A.

Curve C in Figure 7 represents the national mean for all ages for pressure measured under an earphone. Curve C is the accepted standard for audiometers, i.e., the sound pressures indicated by the various frequencies on Curve C are those supposedly generated under an earphone by a standard audiometer when indicating normal hearing.

There are several factors contributing to the difference between Curves A and C. Some of these are:

(a) Curve C is for all ages whereas Curve A is for young observers, whose ears are more acute than those of older people.

(b) For some unknown reason 6 or 7 db more sound pressure must be produced at the eardrum by earphones than by a loud speaker at a meter's distance to achieve threshold.

(c) Two or 3 db less pressure is required for threshold when both ears are exposed to sound than when one ear is exposed (*103*).

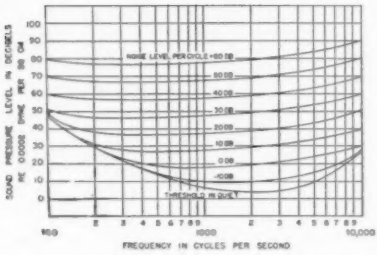

FIGURE 8. Monaural thresholds for pure tones when masked by various levels of white noise having uniform energy per cycle. From Miller, Wiener and Stevens (*130*), after Hawkins, Garner and Miller (*56*).

The problem of the absolute threshold is a tricky one, but for many engineering purposes these differences among threshold measures must be taken into account.

The Masked Threshold. Functions relating the intensity required for persons with normal hearing just to detect the presence of pure tones of various frequencies in quiet and in noise are presented in Figure 8. In obtaining these results, tones and noise were presented monaurally through an earphone and the sound pressure measurements were made with a probe tube at the entrance to the ear canal. Masking thresholds were obtained for 16 frequencies between 100 and 9,000 cps in quiet and with eight different levels of masking noise. The

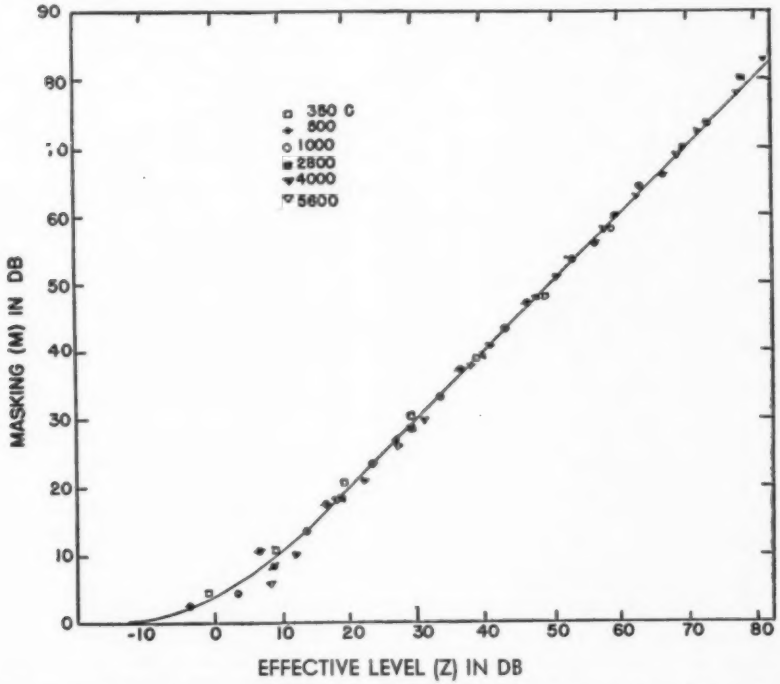

FIGURE 9. Relation between masking (M) and the effective level (Z) of the masking noise. From Miller, Wiener and Stevens, (*130*), after Hawkins, Garner and Miller (*56*).

noise used contained nearly all frequencies over the audible range and each frequency between 100 to 9,000 cps carried on the average the same energy. Such a noise is called 'flat,' 'white' or 'thermal' by various writers. Steam escaping from a radiator often makes a white or flat noise.

The lowest contour in Figure 8 is the *absolute* threshold curve and the upper curves represent *masked* thresholds. The masking effect of noise can be considered as a shift of threshold. The amount of masking is measured by the extent to which the threshold of detection for pure tones or for speech is elevated above the quiet or absolute threshold. The data of Figure 8, when plotted as in Figure 9, reveal that, except near threshold, the masked threshold goes up linearly as the intensity of the noise is raised. Previous results from Bell Telephone Laboratories (*38*) show, on the contrary, a non-linear relationship above an effective noise level of 50 db. Effective noise level or 'Z' is the level in db above threshold for the 'critical band.' This latter term will be defined later.

This notion of a shift in threshold can be extended to speech perception. Figure 10 shows the articulation obtained with a high fidelity communication system and various levels of masking noise. The abscissa gives the intensity level of the speech in db above the absolute threshold for speech under quiet conditions. The

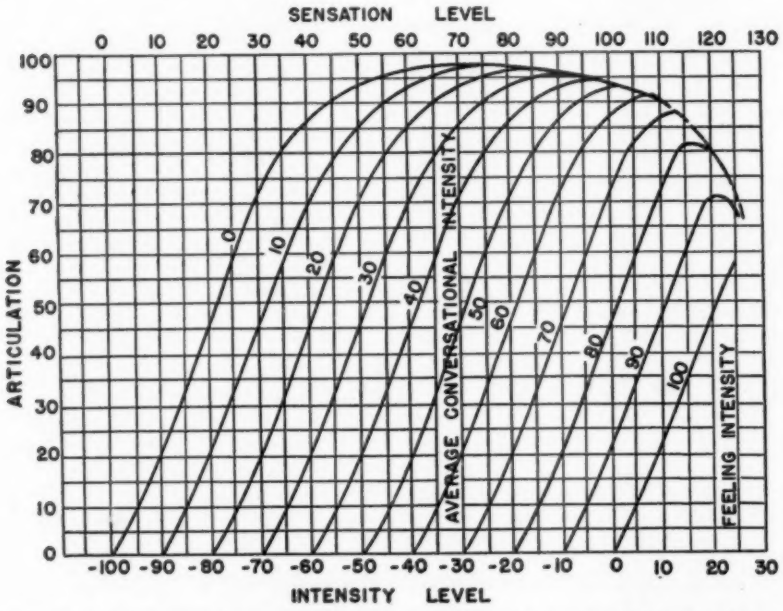

FIGURE 10. Relationship between speech intensity level and per cent syllable articulation. The parameter is intensity of white noise in db re threshold of detectability. As the noise intensity is raised 10 db, the articulation function is shifted approximately 10 db to the right. The ordinate on the top of the graph gives the sensation level of speech in db. From Fletcher (*37*), by permission of D. Van Nostrand Co., Inc., and Bell Telephone Lab.

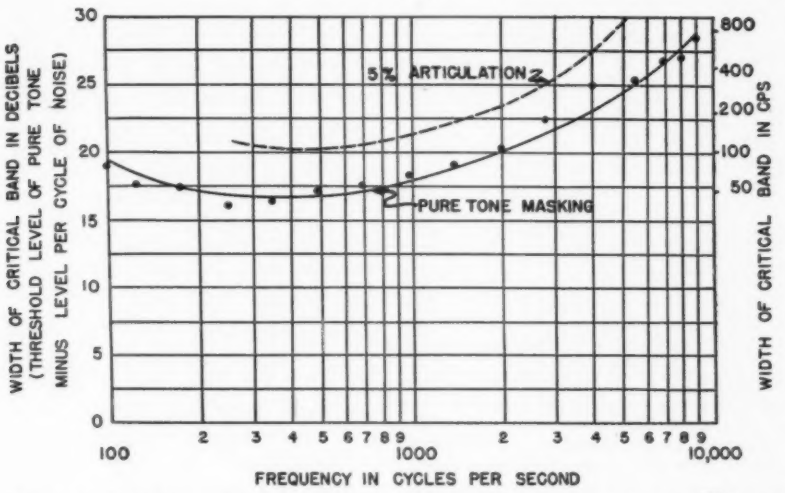

FIGURE 11. Ratio between the monaural masked threshold of a pure tone and the level per cycle of the masking noise measured at the frequency of the pure tone. Solid line, data obtained at Bell Telephone Laboratories; points, data obtained on this relationship at Psycho-Acoustic Laboratories. The dashed curve is a smoothed curve showing the width of equal (5 per cent) articulation bands plotted against the center frequency of each band. The ordinate on the left gives the width of the critical band in cycles per second. From Miller, Wiener and Stevens (*130*), after Hawkins, Garner and Miller (*56*).

absolute threshold for speech or 'threshold of detectability' corresponds roughly to zero intelligibility. The number on each curve gives the intensity of noise present for each particular curve. The noise is measured in terms of the number of db it raised the threshold of detectability of the speech. The noise had a continuous or 'white' spectrum.

The bending down in the articulation curves in Figure 10 at the higher speech levels has been attributed to 'overloading' and to nonlinearity of the ear at the higher intensity levels.

The intelligibility of speech rises at a fairly constant rate above the threshold of detectability regardless of the absolute level of the noise. Raising the level of speech to 25 db above the threshold of detectability, for example, results in approximately 50% articulation in each intensity of noise; the masking or background noise has no effect on the intelligibility of speech when the wanted pure tone or speech signal is sufficiently above the noise. There is a practical limit to this principle, however. Very intense sounds are uncomfortable or even painful, and when the masking noise approaches such intensities, it is not possible to make the wanted speech or tone intense enough to be heard and not painful.

The ratios between the intensity per cycle of the masking noise and the intensity of the pure tones at masked threshold for the four top curves in Figure 8 are plotted as points in Figure 11. The solid line represents the results from similar experiments conducted by Bell Telephone Laboratories (*50*).

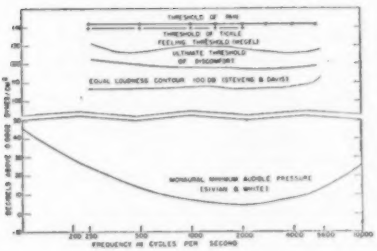
THRESHOLD OF TICKLE
FEELING THRESHOLD (WEGEL)
ULTIMATE THRESHOLD OF DISCOMFORT
EQUAL LOUDNESS CONTOUR 100 DB (STEVENS & DAVIS)
MONAURAL MINIMUM AUDIBLE PRESSURE (DAVIS & WHITE)
DECIBELS ABOVE 0 DYNE/CM²
FREQUENCY IN CYCLES PER SECOND

FIGURE 12. Auditory map for pure tones for normal hearing. The curves in the upper half of the figure represent pressures measured under the receiver by means of a coupler. The lower curve for minimum audible pressure has been corrected to give the pressure at the ear drum. It is, therefore, approximately but not precisely comparable with the upper curves. From Silverman (*113*), with permission of the author and the *Annals of Otology, Rhinology, and Laryngology*, St. Louis, Mo.

If an extremely wide band of masking noise is taken at the minimum intensity required to mask a pure tone located at the middle of the frequency range, the band of noise can be symmetrically reduced in width towards the tone without lowering the masking effectiveness until the 'critical band width' is reached. It is usually assumed that the energy in the narrowed band now equals the energy in the pure tone. Reducing the band width further will require that the energy in the noise be raised if it is still to mask the tone. Each 'critical band' is believed to be independent of masking effects from other adjacent bands since the masking threshold is not altered by the subtraction, or addition, of noise falling outside the critical band. It is probable that the concept of 'critical band width' can be applied to the masking of speech in the same way it is to the masking of tones.

The widths of critical bands are indicated in Figure 11 in terms of db, i.e., the threshold level of the pure tone minus the level per cycle of the noise. The band width in db can be converted into width in cycles since energy in a band of white noise is proportional to the width of the band. Since 20 db represents a ratio of 1 to 100, a 20 db band relative to a pure tone one cycle wide would be 100 cycles wide. Thus, the band centered at 2000 cps and 20 db wide extends from 1950 to 2050 cps.

The Upper Thresholds. Thresholds for discomfort, tickle and pain for normal and hard-of-hearing subjects have been determined at the Central Institute for the Deaf with both pure tones and speech (*113, 114*). The medians of the pure tone thresholds of persons with normal hearing are presented in Figure 12. The corresponding thresholds for speech are given in Table 1. It was found, as is indicated in the table, that tolerance for loud sounds increased during the first several testing sessions so that the final thresholds were somewhat higher than initially. For example, the threshold of discomfort for speech increased from 117 to a final value of about 130 db. The threshold of discomfort for pure tones extends as a broad plateau over the frequency range from 250 to 5,000 cps at about 120 db re .0002 dyne/cm^2.

INTELLIGIBILITY OF SPEECH

On the basis of results from numerous articulation tests, Fletcher, and also French and Steinberg (*50*) of the

TABLE 1. Thresholds of tolerance for speech in decibels re .0002 dyne cm^2.

	Discomfort	*Tickle*	*Pain*
Initial	117	128	138
Final	130	135	139

Bell Telephone Laboratory, has attempted to devise a method whereby the intelligibility of speech can be estimated by means of proper physical measures of the communication system and the noise conditions alone.

Inasmuch as the methods of testing directly the intelligibility of speech are time consuming and require carefully controlled experimentation, this method of calculation could be a very practical device. It should be mentioned that Collard (7), and later Zoldakov (*137*), suggested a number of years previous to publication of the Bell Telephone Laboratory method that such procedures would be valid. Both of them devised methods of computing the intelligibility of speech that are somewhat similar to but not so well founded as the method eventually derived at the Bell Telephone Laboratories, which will be summarized briefly.

Articulation Index (AI). The first step was to divide the audible speech spectrum into 20 'equal articulation bands.' The bands or frequency limits are supposedly set so that each band individually and independently contributes one-twentieth to the over-all articulation index. The Articulation Index (AI) is taken as 1.0 for perfect articulation. Thus, the speech in each of the equivalent bands can contribute no more than .05 to the total index. The frequency limits of each band were determined from articulation tests conducted with filters set at various cut-off frequencies and inserted into an otherwise high-fidelity transmission system. Nonsense syllables, i.e., syllables constructed from consonant-vowel-consonant combinations with meaningful combinations eliminated, were used as the test material. Articulation scores were obtained for intensities of speech from

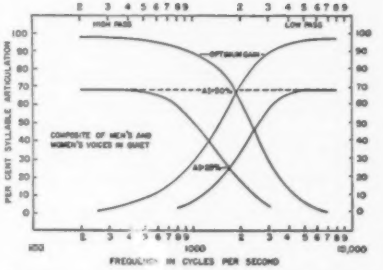

FIGURE 13. Articulation scores vs cut-off frequency of high-pass and low-pass filters inserted in a wide-band system. From Miller, Wiener and Stevens (*130*), after French and Steinberg (*50*).

minimum to optimal and for many filter settings.

Syllable articulation as a function of the cut-off frequency of the filters at two different speech intensities is shown in Figure 13. These curves show clearly that the articulation index must be used rather than simple articulation scores in order to obtain additive speech bands. For example, at optimum gain[2] a system passing only frequencies above 1900 cps (the point of intersection of the two curves) gives as good an articulation score as a system that allows only frequencies below 1900 cps to be passed. The articulation score, however, is not 50% as might be expected but 68%. In other words, an *articulation score* of 68% requires only half of the speech frequencies necessary to achieve 100% articulation. It is therefore given an *articulation index* of 0.5.

Next, articulation scores were obtained for a number of filter settings at an intensity gain that gave a 68% articulation score (.5 Articulation In-

[2]Optimum gain was found to be the speech level (in quiet) that is 10 db more intense than direct conversational speech at one meter's distance from the talker's mouth.

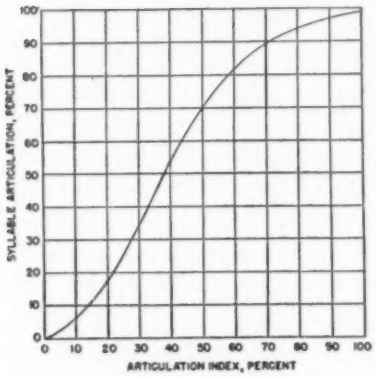

FIGURE 14. Approximate relation between syllable articulation and articulation index. From Miller, Wiener and Stevens (*130*), after French and Steinberg (*50*).

dex) with wide pass-bands. The curves of the results happen to cross (Figure 13) at the 25% articulation score. This articulation score (25%) is given an articulation index of .25, i.e., half of 0.5, because either half of the speech spectrum is enough to obtain this score under conditions which would yield an index of 0.5 if the entire spectrum were used. By similar procedures of fractionation applied to numerous articulation functions, the function in Figure 14 was derived. This function relates articulation score to articulation index expressed in per cent.

By referring to Figure 14 the per cent articulation values of Figure 13 were converted to the articulation index values shown by B in Figure 15. This figure shows the articulation index value in per cent as a function of upper cut-off frequency of a filter inserted in the speech transmission system. Curve A in Figure 15 represents the same function for only male voices. Curve A is now divided into frequency bands, each one of which contributes 5% (.05) to the articulation index. These bands of equal importance to articulation or intelligibility thus revealed are indicated in Table 2 and on the abscissa of Figure 18.

On Figure 11 the width in cycles per second of each of the 20 equal articulation bands is plotted above the center frequency of each band. The similarity in shapes of the two curves in Figure 11 indicates an internal consistency between and lends support to the assumptions underlying the articulation index and the concept of critical band width.

It is of theoretical significance that the shape of the curves in Figure 15 are similar to that of the pitch scale (*122*), to the function relating position of maximum agitation on the basilar membrane to the frequency of the stimulating tone, and to a function relating critical band width to frequency.

Relationship Between Articulation Index and Articulation Scores. It is clear that the relationship between per cent articulation and articulation index is dependent upon the type of test material used. Different talkers and

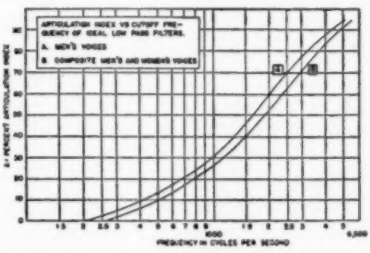

FIGURE 15. Articulation index versus cut-off frequency of ideal low-pass filters as determined by French and Steinberg (*50*). From Beranek (*2*), with permission of the author and the Institute of Radio Engineers, New York City.

TABLE 2. Frequency bands of equal contribution to articulation index (for male voices).

No.	*Limits*	*Mean*
1	200 to 330	270
2	330 to 430	380
3	430 to 560	490
4	560 to 700	630
5	700 to 840	770
6	840 to 1000	920
7	1000 to 1150	1070
8	1150 to 1310	1230
9	1310 to 1480	1400
10	1480 to 1660	1570
11	1660 to 1830	1740
12	1830 to 2020	1920
13	2020 to 2240	2130
14	2240 to 2500	2370
15	2500 to 2820	2660
16	2820 to 3200	3000
17	3200 to 3650	3400
18	3650 to 4250	3950
19	4250 to 5050	4650
20	5050 to 6100	5600

listeners also cause minor differences. Articulation index can be converted to word (polysyllables) or to sentence intelligibility, however, by using the curves shown in Figure 16. Results of tests (unpublished) conducted at the Psycho-Acoustic Laboratory have shown that the special monosyllabic word tests (the so-called 'phonetically balanced' or 'PB' lists) constructed at that laboratory are about equivalent in difficulty (for well-trained listeners) to the nonsense syllable tests used at the Bell Telephone Laboratories.

Relationship Between Speech-to-Noise Ratio and Articulation Index. In order to calculate the total articulation index for a given communication system the intensity of speech and of masking noise in each of the 20 bands of equal articulation must be measured physically. Since the dynamic range between rms pressures of speech is about 30 db (Figure 4), the speech intensity must exceed the masked threshold by 30 db or more if the weakest speech sounds are to be audible. Per cent articulation does not increase linearly with speech intensity (see Figure 10), however, but gradually tapers off at very weak and high intensities.

On the basis of the data gathered in the development of the articulation index the weights (W_p) given in Figure 17 were derived. 'B_g' indicates the long average speech, and 'B' the long average noise intensity. The long average of speech falls approximately 12 db below the rms intensities occurring in 1% of one-eighth second intervals (Figure 4), but the average intensity of the continuous 'white' noise is constant for one-eighth second intervals; for this reason 12 db has been subtracted from signal-to-noise ratios determined from long average measurements of intensity in order to properly determine weights for Figure 17.

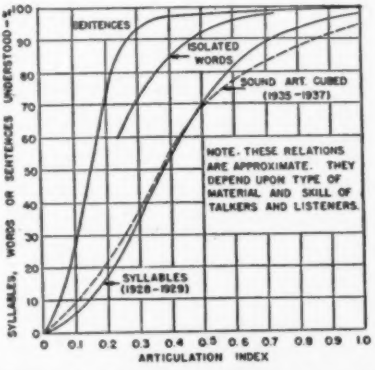
SENTENCES
ISOLATED WORDS
SOUND ART CURED (1935-1937)
NOTE- THESE RELATIONS ARE APPROXIMATE. THEY DEPEND UPON TYPE OF MATERIAL AND SKILL OF TALKERS AND LISTENERS.
SYLLABLES (1928-1929)
SYLLABLES, WORDS OR SENTENCES UNDERSTOOD - %
ARTICULATION INDEX
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
0 10 20 30 40 50 60 70 80 90 100

FIGURE 16. Approximate relations between articulation index and subjective measure of intelligibility. From French and Steinberg (*50*), with permission of the author and the Acoustical Society of America, Washington, D. C.

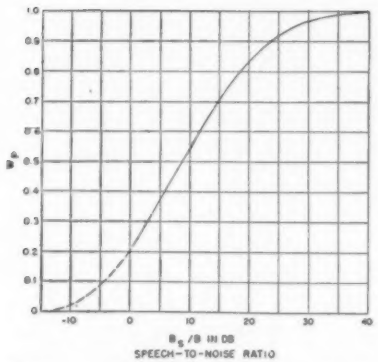

FIGURE 17. Weighting factor vs speech-to-noise ratio. From Miller, Wiener and Stevens (*130*), after French and Steinberg (*50*).

A weight of 1.0 is therefore given to each of the 20 articulation bands in which the speech sufficiently exceeds the masking noise (or the absolute threshold if there is no noise present). A proportional fractional weight is given if the difference is less.

Articulation Index Work Sheet. Beranek (*2*) has devised a work sheet (Figure 18) that is useful for computing the articulation index of a communication system. The numerical values for the frequency bands on his work sheet are based on data for men's voices only.

It is to be noted on this work sheet that the spectrum level (the intensity per cycle) of the speech must not exceed about 95 db above .0002 dyne/cm². Since the speech has a continuous spectrum, the over-all intensity will be about 125 db when the spectrum values are 95 db above .0002

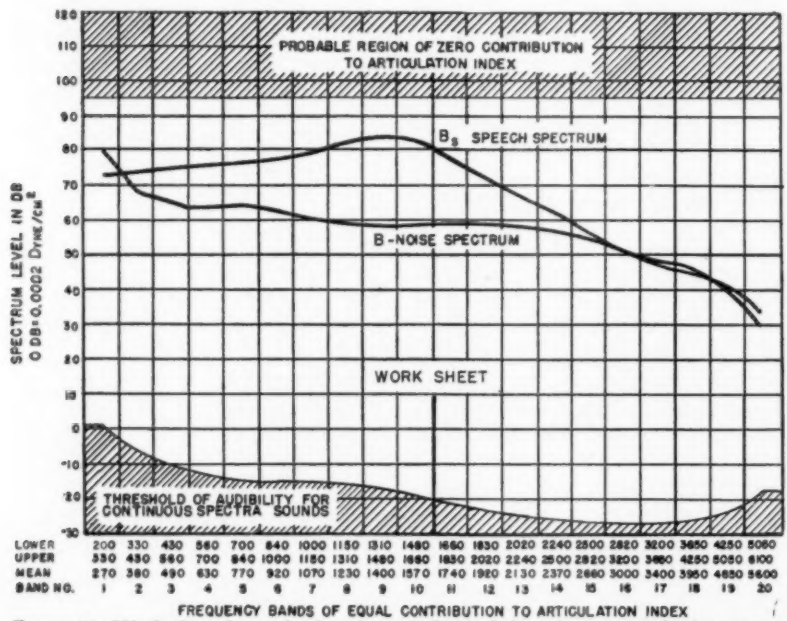

FIGURE 18. Work sheet for evaluating the articulation index of a communication system with noise present. From Miller, Wiener and Stevens (*130*), after Beranek (*2*).

dyne/cm². This approaches the threshold of tickle and pain and for that reason, as well as because intelligibility normally begins to decrease at such high intensities, the spectrum intensity should not exceed 95 db. An increase above 95 db probably makes no additional contribution to the articulation index.

If the articulation index is used for the calculation of speech intelligibility, it must be certain that the measurements of the speech and noise reaching the listener's ears are expressed in comparable terms. This often requires a considerable number of operations. If there is, for example, an aircraft interphone system involving a microphone, amplifier, earphone and earphone cushions, the following must be determined:

(1) The noise pressure in the outer ear canal of the listener due to noise picked up by the microphone and amplified by the interphone. Determinations of the speech-to-noise ratio for various military microphones when used in noise can be found in a report by the Electro-Acoustic Laboratory (*30*).

(2) The noise pressure in the outer ear canal due to the noise that leaks in around the earphone cushion. The noise reaching the ear when various types of earphone cushions are worn in an ambient noise field can be calculated on the basis of attenuation measurements made at the Psycho-Acoustic Laboratory by Shaw (*111*).

(3) The 'real voice' objective response of the microphone. This is the voltage produced by the microphone across a resistive load when it is activated by a human voice operating at conversational level. 'Conversational level' is loud enough to produce an over-all rms level of 74 db re .0002 dyne/cm² at a distance of 1 meter from a talker in an anechoic (non-reverberant) chamber. The speech used for this purpose is often the sentence, 'Joe took father's shoe bench out; she was waiting at my lawn.'

The output of the microphone is fed into a number of band pass filters so that measurements of intensity may be made for a number of frequencies or narrow bands of frequencies throughout the speech spectrum. There appears to be no well-defined method of how to read the meters indicating intensity; usually, however, rms readings are taken for each word uttered and then averaged.

(4) The 'real ear' objective[3] response of the earphone. This is the sound pressure produced in the ear canal of an average listener as a function of frequency and with constant voltage applied to the terminals. The measurements must be made with a small probe tube inserted into the entrance of the listener's ear canal.

(5) The response characteristic of the amplifier to audible frequencies. This is the input-output characteristic of the amplifier as a function of input frequency.

The figures for 3, 4 and 5 are then added together to get the spectrum level of speech. This represents what is called the 'orthotelephonic gain.' A constant of 12 db should be added if

[3]Real ear *subjective* calibrations may be used in place of the objective measures. The listener adjusts the intensity of a pure tone from the earphone until it sounds as loud as a pure tone of the same frequency coming from a loud-speaker that is one meter away from him in a free field. The intensity of the tone from the loud-speaker is measured at the position occupied by the listener's head. When subjective earphone calibrations are used it is important that noise leaking around the earphone cushion be measured by similar methods.

the intensity measures are taken over an appreciable period of time to take into account the rms intensities that occur in one-eighth second intervals one per cent of the time. The result is the speech spectrum to be plotted on the work sheet. It is to be noted that the orthotelephonic gain involves a specified 'conversational' voice level. For the 'real voice' measures of microphones, Beranek (2) recommends that talkers speak at 'half effort' in the quiet of an anechoic chamber. When the talker is operating in the noise, however, it is possible that his voice level will be considerably above the conversational or half-effort level (*69*). This is one possible reason for the divergence between the obtained and calculated articulation scores presented below.

An alternative way to obtain the speech spectrum is to use calibrations of earphones made on artificial ears and of microphones made with an artificial voice. The response characteristics thus obtained are added to the uppermost idealized voice spectrum given in Figure 4. The sum is the speech spectrum to be plotted on the work sheet. Although certain interactions between a live voice and microphone and between the human ear and earphone are not reflected in the 'artificial' physical calibrations, the more tedious 'real' v o i c e and ear measurements are thereby avoided. In reference *30* there will be found a host of artificial voice and ear calibrations of various military and commercial microphones, earphones and amplifiers that can be used for this purpose.

(6) The noise s p e c t r u m to be plotted on the work sheet is a summation of the noise reaching the ear through the communication system and from all other sources. This summation can be done in terms of the root - mean - square pressures of the noises involved.[4]

(7) The differences in db between the resulting spectra of noise and of speech at the midpoint of each equal articulation band are taken. The corresponding weights (W_p) are taken from Figure 17. The weight for each of the 20 bands is then multiplied by .05. The sum of these products is the total articulation index. The assumption that the same weights can be applied regardless of absolute speech and noise levels within the limits indicated on the work sheet, is based on the linearity of the masking function shown in Figure 11.

By use of Figure 16 the *articulation index* can finally be converted into *per cent articulation* or intelligibility scores.

Obtained vs. Calculated Articulation Scores. Egan and Wiener (*29*) conducted a series of syllable articulation tests wherein a variety of bands of speech were transmitted by the communication system. A noise of constant i n t e n s i t y and continuous spectrum was present during most of the testing. From these data they derived generalized equal - articulation contours that show the relationships among frequency distortion of a communication system, the intensity level of speech and the resulting syllable articulation (see Figure 19).

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[4]The Bell Telephone Laboratories (*50*) have determined the value of two other factors in speech reception that may be included in the noise spectrum, although they are relatively insignificant compared to the effects of noises usually present from other sources: (a) the masking effect of one band of speech on other bands, and (b) the temporary deafening caused by speech peaks.

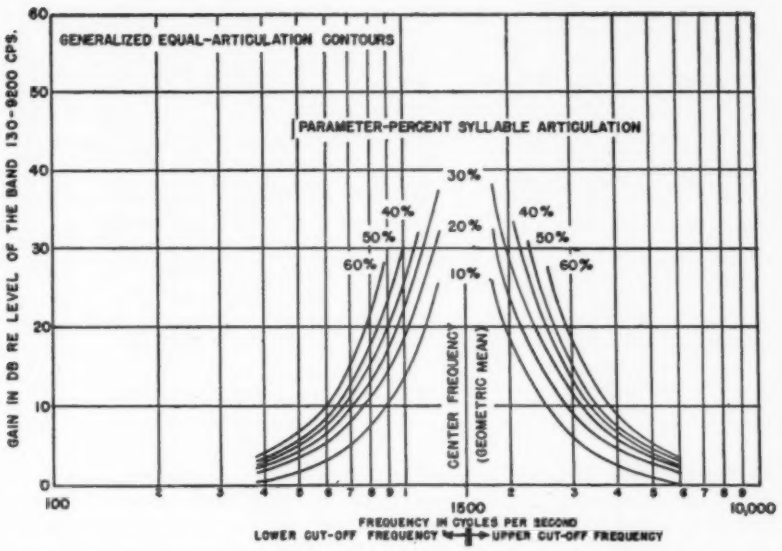

FIGURE 19. Generalized equal-articulation contours plotted for band-pass systems all having a center frequency of 1500 cps. The same contours may be used to predict the relative performance of pass bands having other center frequencies, provided the family of contours is shifted horizontally to make them correspond to the new center frequency. From Egan and Wiener (29).

The results of this experiment would appear to afford a good test of the method of calculating articulation and Beranek (2) has made the necessary computations. His findings are shown in Figure 20. The agreement between actual and computed articulation is not as close as might be desired for some of the pass-bands.

Beranek also compared the calculated articulation scores with actual articulation data obtained on a number of interphone systems operating at various gain levels in B-25 and B-17 bombers (75). The results are presented in Figure 21; it is seen that the agreement here is rather close.

Beranek concludes that a communication system having an articulation index greater than .5 will give satisfactory intelligibility of speech, while a system with an articulation index of lower than .3 should be considered

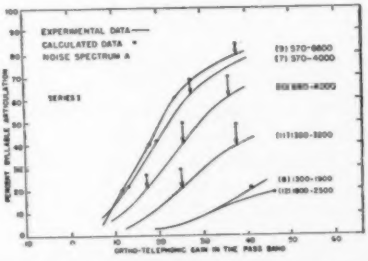

FIGURE 20. Comparison of experimentally determined and calculated articulation scores for speech transmission systems numbers 7 to 12 in noise spectrum A. From Beranek (2), with permission of the author and the Institute of Radio Engineers, New York City.

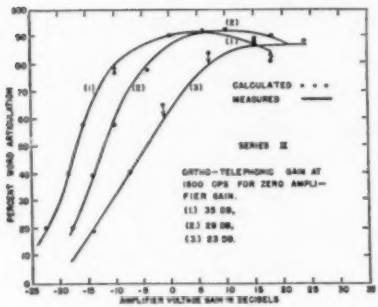

FIGURE 21. Comparison of experimentally determined and calculated articulation scores for three types of interphone systems in an untreated bomber. From Beranek (2), with permission of the author and the Institute of Radio Engineers, New York City.

unsatisfactory in that regard. Systems falling between .3 and .5 should be viewed with suspicion. Beranek's reasoning here is probably based on the curves shown in Figure 16 which depict the relationship between intelligibility of sentences, words and syllables and the articulation index. An examination of this figure reveals that over 93% of isolated words and over 98% of sentences would be correctly understood with an articulation index of .5 or higher; for an articulation index of .3 about 73% of isolated words and 93% of sentences would be heard correctly whereas below .3 the curves drop precipitously. Therefore, communication systems falling between .3 and .5 would permit reasonable sentence intelligibility, but would have a small margin of safety and a significant number of isolated words would be misunderstood. Below an articulation index of .3 intelligibility even for sentences would be close to the 'breaking' point.

Limitations of the Method. It appears that the Bell Telephone Laboratories' method of calculating articulation is accurate enough to warrant its use under certain conditions. Some of the assumptions and propositions, however, are subject to further proof. The originators of the method have pointed out that (1) the Articulation Index does not take into account effects of nonlinear (amplitude) distortion, (2) the masking effects when the noise is intermittent cannot be considered, and (3) the method is workable only if the noise is of the continuous spectrum type or not too far removed from it. As stated previously, the calculation of articulation or intelligibility as presented here is based, in part, on the assumption that the 'critical bands' of masking, shown in Figure 11, are really independent and that masking effectiveness increases linearly with increases in intensity. It is well known (see Figure 22), however, that a pure tone will mask higher frequencies to a greater degree than it masks frequencies falling below its own frequency. Also, the more intense the tone, the greater is the masking 'spread.' The question might be raised, then, as to why the concept of critical bands for masking is valid for noise with a fairly continuous spectrum. Apparently, with pure tones the spread of masking to higher frequencies is due, in part at least, to distortion products introduced by overloading the ear, but with noise of continuous spectrum the distortion products of the lower frequency components are insignificant in comparison to the masking afforded by the actual noise already present at the higher frequencies. Just how far from 'flat' the noise may be before the method fails on this account has not been determined.

In a recent study Pollack (*104*) measured the intelligibility of speech when passed through a variety of

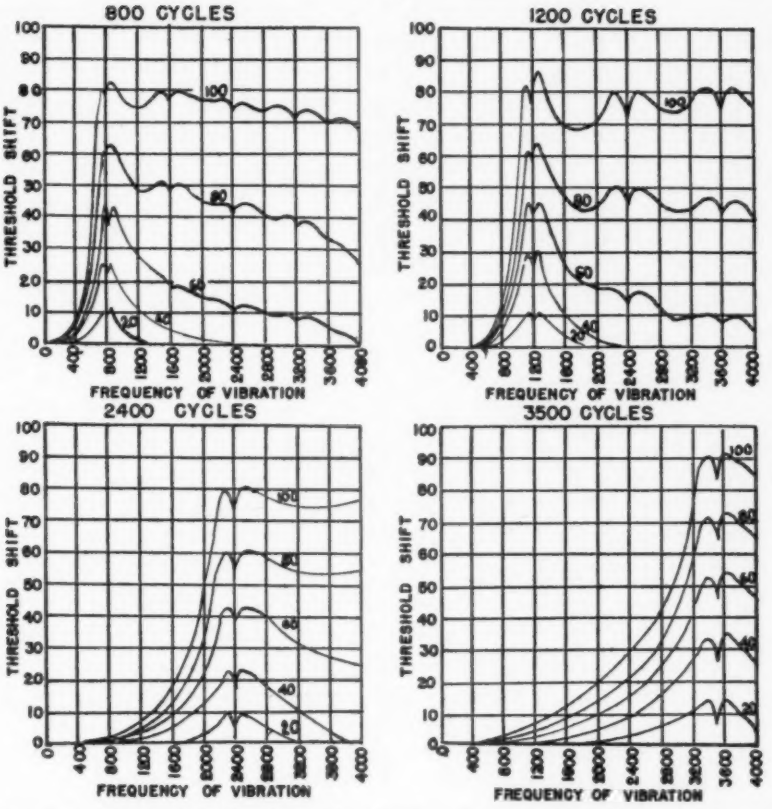

FIGURE 22. The threshold shift in db of various pure tones just detectable in the presence of a steady pure tone of frequency indicated at the top of each graph. The parameter is the sensation level of the masking tone and is indicated in db on each curve. From Fletcher (37), by permission of D. Van Nostrand Co., Inc., and Bell Telephone Lab.

high-pass and low-pass filters at various intensity levels in the presence of noise. He found that the Bell Telephone Laboratories' method of computing speech intelligibility was valid for the majority of his test conditions. It appeared, however, that the intelligibility conveyed by the low frequencies was not constant with constant signal-to-noise ratio, as the computational method assumes, but varied somewhat as a function of the overall intensity level. Also, he points out that the proposed computational procedures do not take into account possible interactions between noise and voice levels used by talkers. In noise, a talker unconsciously raises his voice to help override the noise.

Typical Noise Encountered in Industry and in Military Vehicles. Octave-band measurements have been

made of noise found aboard various military vehicles and in some industries. Examples of these measurements are to be found in Figures 23 and 24. The noise analysis in Figure 23 for the Liberator Bomber represents the noise present in the articulation tests that yielded the results given in Figure 21. Here the agreement between calculated and actual test scores was rather close. It is probable that under most of the noise conditions shown in Figures 23 and 24 the noise is sufficiently continuous in spectrum so that the Bell Telephone Laboratories' method can be used to predict articulation in its presence.

Special Tests of Intelligibility of Speech in Noise

While the Bell Telephone Laboratories' method of computing the intelligibility of speech is not as general a method as might be desired, its presentation has brought together many important experimental facts concerning the intelligibility of speech in noise. Some other results dealing with

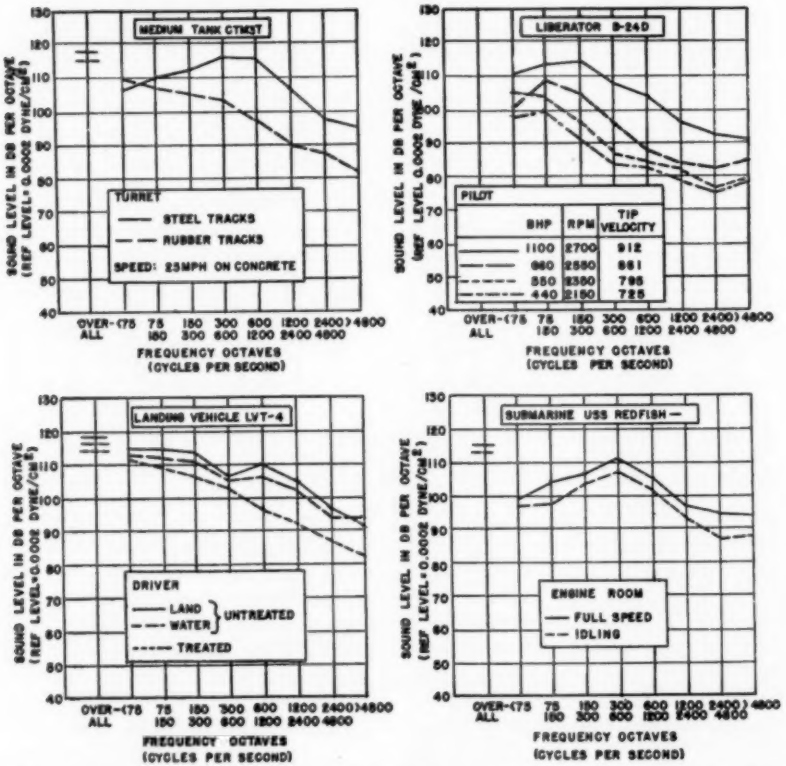

Figure 23. Noise levels and spectra in the turret of a medium tank, a Liberator Bomber, Landing Vehicle LVT-4, and a USS Submarine. From Miller, Wiener and Stevens (*130*).

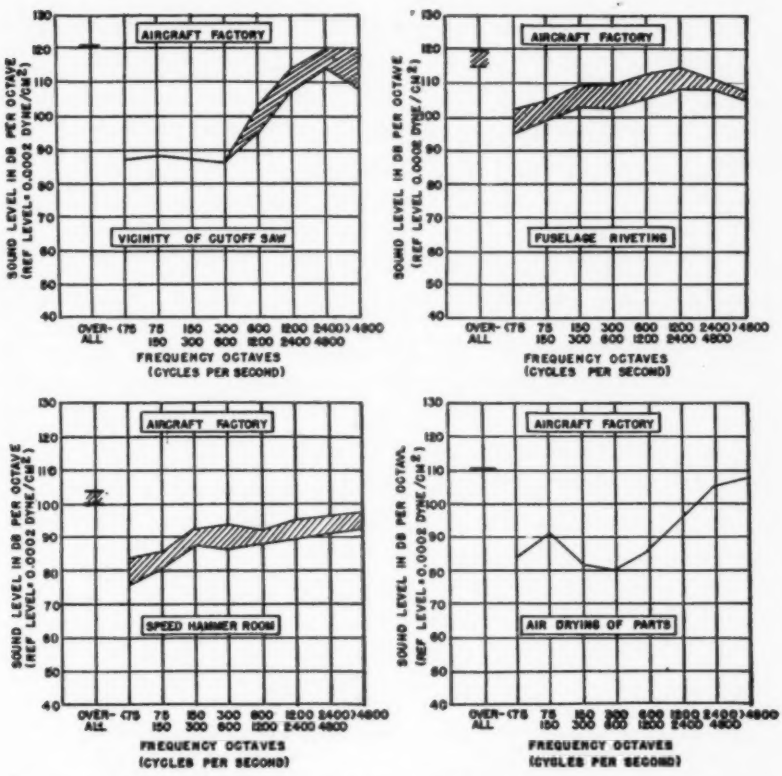

FIGURE 24. Noise levels and spectra in an aircraft factory. From Miller, Wiener and Stevens (*130*).

the effects of special treatments of the speech signal, the noise, or methods of presenting the speech and noise are presented in the next sections.

Effect of Intermittent Noise. So far the effects of a continuous uninterrupted noise have been considered. Miller and Mitchell (*89*) have found that interrupting the noise but leaving the speech continuous greatly reduces the masking effect of the noise. The nature of speech is such that the speech can be obliterated, either with a masking noise or by being turned off directly for over 25% of the time without significant loss of intelligibility. As the fraction of the time the noise is on is increased, its masking efficiency increases directly as shown in Figure 25 (*130*). The abscissa in Figure 25 is the ratio of speech intensity to noise, which was varied. The over-all noise intensity was kept constant for all tests. The parameter is the percentage of time the noise was on.

In situations where both the noise and speech are intermittent it is, of

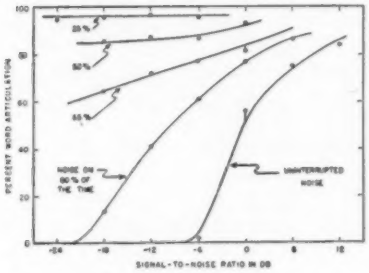

FIGURE 25. Masking efficiency of a noise signal which is interrupted for different proportions of the time at a rate of nine interruptions per second. From Miller, Wiener and Stevens (*130*), after Miller and Mitchell (*89*).

course, possible to predict the intelligibility of speech only in a statistical sense.

Amplitude Distortion. The effects of non-linear or amplitude distortion which can be present in any or all the component parts of an electrical communication system have not been given as much attention as those of frequency distortion, which was the primary concern of the Bell Telephone studies. And, interestingly, properly controlled amplitude distortion may be a useful technique for improving the intelligibility of speech in the presence of noise.

Licklider (*71*) was the first to test exhaustively the effects of various kinds of amplitude distortion on the intelligibility of speech, although previous observations had been made at the Bell Telephone Labortories (*37*). He found, among other things, that by peak-clipping the peaks of speech as much as 24 db (thereby essentially reducing the vowel-consonant ratio [Figure 6]) and by amplifying the resulting signal to its former peak value the quality of the speech was not greatly affected. Also, in the presence of noise and in quiet, the speech thus treated was *more* intelligible at many intensities than undistorted speech of *comparable peak amplitude* (see Figure 26). This is possible because the weak consonant sounds have been increased in intensity and made more audible, although the over-all peak intensity of the speech has not been increased. Thus, by limiting the maximum amplitude of the speech to a level just below discomfort, (a) the

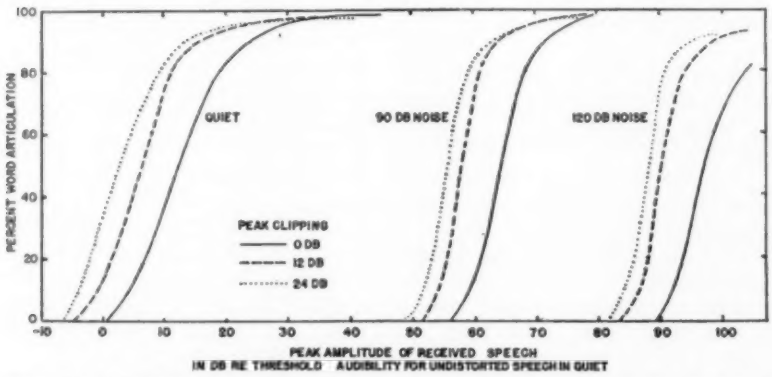

FIGURE 26. Functions relating articulation to peak amplitude of received speech with peak clipping and background noise as parameters. From Licklider (*71*).

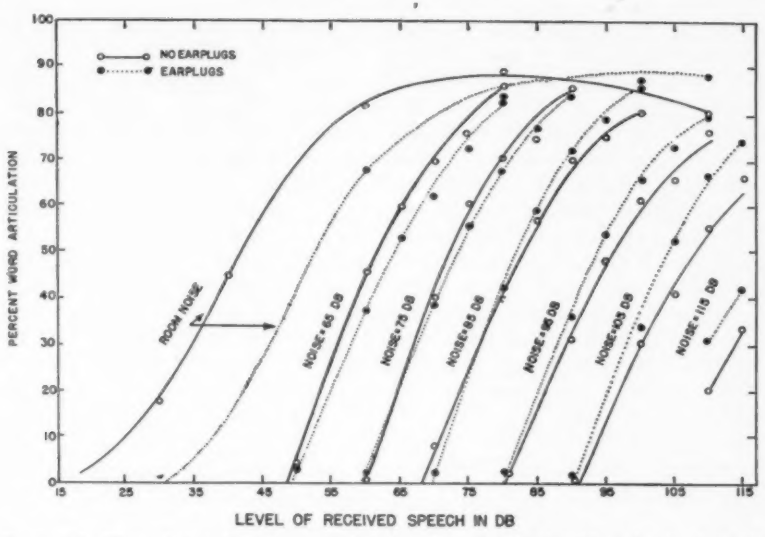

FIGURE 27. The relation between articulation and speech level with noise level as the parameter. In loud noise ear wardens improve articulation. From Kryter (*65*).

listener's ears can be protected, and (b) the area of audibility remaining in the presence of a loud masking noise can be used to a fuller extent than is normally possible. Also, and what is effectively the same thing, the reduced auditory area of a person who is suffering from certain types of deafness can be used more effectively.

Proper application of peak-clipping (or compression) of the speech signal is clearly one method for improving communication in the presence of intense noise, and indeed is being used in some recently designed audio and radio equipment. The amount of peak-clipping to be applied depends on a number of factors, such as type and source of noise, the frequency distortion in the communication system, etc., and it is not possible to name one single optimal amount (*67*, *68*, *71*).

Effects of Wearing Ear Plugs on Speech Intelligibility. One simple and effective way of reducing the effects of intense noise is to wear ear plugs. Suitable ear plugs have been developed and the effects of wearing the NDRC 'type V-51R' plug, which was adopted for use by the Army and Navy, upon the intelligibility of speech, has been investigated (*66*). The results of these tests are shown in Figure 27. Wearing ear plugs in the presence of intense noise does not lower the intelligibility of speech, but slightly *improves* it in the higher noise levels. This is understandable because the plugs in no way alter the signal-to-noise ratio but merely lower the effective level of both the speech and noise by about 20 db.

The attenuation is sufficient to reduce intense noise and speech to a more tolerable level, perhaps to avoid non-linear distortion of intense speech

sounds by the ear itself, and to minimize any 'glare' effect of noise. 'Glare' effect here refers to a temporary reduction of the power of auditory discrimination by very intense sound.

Influence of Interaural Phase Relations on Intelligibility of Speech. In the experiments discussed so far, it has been assumed that the intelligibility of speech in noise is essentially a function of the signal-to-noise ratio at the listener's ears. When ear phones are a part of the communication system, however, a number of phase relationships between the sound waves reaching the two ears are possible and it has been found that intelligibility is somewhat dependent upon these phase relationships.

Licklider (*73*) examined by means of intelligibility tests the effects of interaural phase relations upon the masking of speech by white noise. His classification is shown in Table 3.

Class 1, homophasic + +, is best illustrated by a communication system that involves earphones. Normally in such a system the two earphones for each listener are wired so that, when activated by a signal, the diaphragms move together towards or away from the ear. Class 5, homophasic — —, can be achieved by reversing the wires on one earphone, so that now the diaphragms when activated by the same signal, move in opposite driections with respect to the ears.

Class 2, + —, and 4 — +, describe the antiphasic interaural relationship that can be accomplished only by a system having a separate amplification channel for each earphone, and separate speech and noise inputs for each channel. Here, if the speech (noise) wave reaching the right ear is in phase with the wave at the left ear, the noise (speech) wave is adjusted to reach the ears 180 degrees out of phase.

In Classes 3, + 0, and 6, − 0, called heterophasic, the earphones were wired to present the speech either in or out of phase, but the noise reached the two ears with random phase relations. From moment to moment the phase relations for noise at the two ears change at random to give any relation between completely in phase and completely out of phase.

The results of the articulation tests are presented in Table 4. For listening in a relative quiet field, but with noise emanating from the earphones, considerable improvement over the standard homophasic condition results if the interaural relationship is made antiphasic. If noise is randomly phased, it apparently does not matter whether the speech reaches the two ears in phase or out of phase.

TABLE 3. Classes of interaural phase relations involving speech and white noise.

Speech	*Noise*	*Symbol*	*Class*
1. In phase	In phase	+ +	Homophasic
2. In phase	Out of phase	+ −	Antiphasic
3. In phase	Random phase	+ 0	Heterophasic
4. Out of phase	In phase	− +	Antiphasic
5. Out of phase	Out of phase	− −	Homophasic
6. Out of phase	Random phase	− 0	Heterophasic

TABLE 4. The influence of interaural phase relations upon the intelligibility of speech in noise (*73*).

Experiment	*Speech-to-noise ratio*	*Noise level (re 0.0002 dyne/cm²)*	1 (+ +)*	2 (+ −)*	3 (+ 0)*	4 (− +)*	5 (− −)*	6 (− 0)*
			Per cent word articulation					
1	0 db	90 db	69.4	77.4	73.6	79.4	68.4	72.3
1	−10 db	90 db	14.4	40.3	29.7	43.7	11.3	27.9
2	−10 db	80 db	18.0	35.4	27.4	43.0	15.8	27.3

*The first symbol refers to speech waves, the second symbol refers to noise waves; + in phase, − out of phase, 0 random phase.

It is clear that masking of speech by noise is more than a simple function of signal-to-noise ratio, and that masking is related to a physiological and psychological reaction to interaural phase relations. Interestingly, it was found that usually there was a strong correlation between the degree of masking and the subjective impression of 'overlapping' of the speech

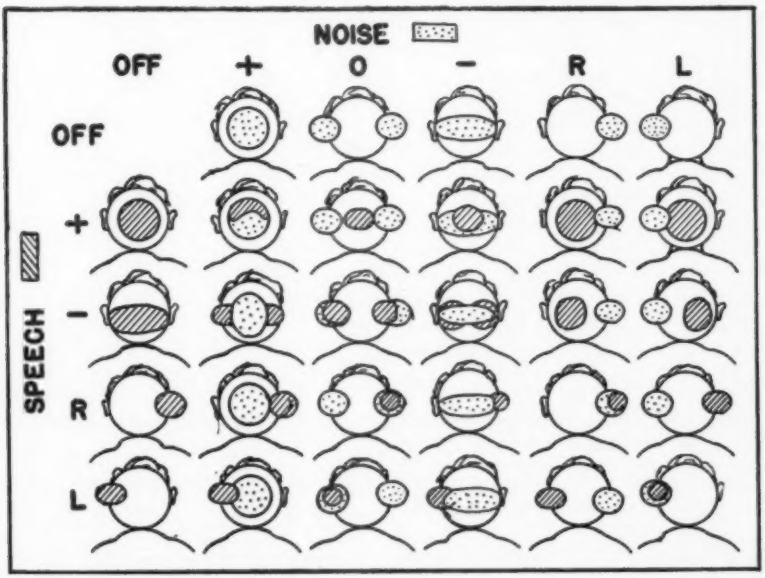

FIGURE 28. Diagram illustrating the influence of interaural phase relations upon the localization of speech and white noise in phenomenal space. Each circle represents a rear view of the listeners' head. The region in which the speech is heard is cross-hatched; the region filled with noise is dotted. From Licklider (*73*), with permission of the author and the Acoustical Society of America, Washington, D. C.

and the noise in the listener's head. The speech and noise sounded as though separated under certain conditions but seemed to occupy the same phenomenal space with other phase conditions. A comparison of Figure 28 with Tables 4 and 5 illustrates the possible relation between the intelligibility of speech and the proximity of speech and noise in 'the listener's head.'

The question is raised as to how closely the various test 'classes' resemble standard operating situations. The answers are:

(a) The antiphasic condition, which provided for the highest intelligibility scores, is artificial in that normally the speech and noise signals are mixed electrically in the interphone and cannot be controlled separately, as is required to achieve the antiphasic relationship.

(b) The heterophasic class with randomly phased noise is also artificial, although it is partially realized when speech is presented via earphones to a listener in ambient, 'field' noise such as in an airplane or engine room. Because of the distance between the ears and the length of sound waves, however, ambient noise is not randomly phased in the real life condition. Rather, the low frequencies tend to be in phase whereas higher frequencies tend to be out of phase at the two ears. The experimental heterophasic classes, then, with completely randomly phased noise are not true representations of ambient noise conditions. Licklider found in some preliminary tests that in actual ambient white noise the articulation scores were approximately five percentage units higher with the connections of one earphone reversed than with the usual in-phase arrangement of the earphones.

(c) The homophasic is representative of the natural condition where circuit and/or static noise emanates from the earphones along with speech signals.

Monaural vs. Binaural Listening. It is fairly common to see a radio operator aboard a plane or ship wearing only one earphone, the other phone being stuck on top of his head. The question arises as to how monaural compares with binaural listening for intelligibility.

Egan (*22*) and Hirsh (*57*) have investigated several aspects of this problem but nearly all the possible variations were studied by Licklider (*73*) in a single experiment and his findings are presented in Table 5. This table shows that the interaural phase relations of the noise and speech have a critical effect on the intelligibility of

TABLE 5. Monaural-binaural presentation and interaural phase relations as factors influencing the masking of speech by white noise.*

		Binaural Noise			*Monaural Noise*	
		+	0	−	R	L
Binaural Speech	+	18.0	27.4	35.4	98.0	99.0
	−	43.0	27.3	15.8	98.1	98.8
Monaural Speech	R	30.3	13.2	20.1	16.6	98.7
	L	18.1	8.3	15.2	98.4	15.4

*Key: + in phase; − out of phase; 0 random phase; R right ear; L left ear.

speech. Three conclusions to be drawn are: (1) noise alone in one ear does not mask speech presented alone in the other ear[5], (2) turning off in-phase speech in one ear, but leaving in-phase noise continuous in both ears, causes an increase in the articulation score from 18 to 30.3 per cent. This represents again an artificial condition for, with standard interphone equipment, the speech cannot be turned off in one ear independently of interphone noise. (3) Except as stated in conclusion 2, the binaural presentation of speech gives better intelligibility than monaural presentations. The articulation scores may be compared to the degree of subjective overlapping of speech and noise in the head, illustrated in Figure 28.

Reverberation. In an ordinary room, or in any enclosure with hard-surfaced walls, speech signals presented either person-to-person or through a loudspeaker will 'generate' noise that interferes with intelligibility. This effect is, of course, due to the reverberation of speech from wall to wall, ceilings and floor. The echoes from preceding sounds tend to mask succeeding sounds as they reach the listener.

Reverberation in a room is measured, usually, in terms of the time required for an abruptly terminated tone to decay 60 db in intensity (*37*). Reverberation time is thus an indirect measure of noise due to reverberation.

Fletcher (*37*) presents an apparently idealized curve for speech articulation as a function of reverberation time (Figure 29). Other data on this effect can be found in reference *64*.[6]

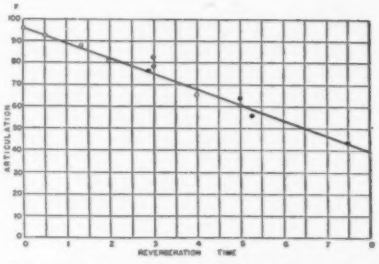

FIGURE 29. Per cent articulation vs reverberation time in seconds. From Fletcher (*37*), by permission of D. Van Nostrand Co., Inc. and Bell Telephone Laboratories.

General Conclusions

Probably the most deleterious effect that noise has on man's behavior is the disruption or 'masking' of speech communication. It would be desirable to be able to engineer, on the basis of physical measures, electronic communication systems that would provide satisfactory intelligibility of speech in the presence of intense noise. A method has been derived whereby an 'Articulation Index' or 'Speech Intelligibility Index' can be computed from careful physical measures of the signal coming from any particular communication system and of the noise in which that system is operated.

[5]Egan (*22*) found that a white noise of moderate intensity in one ear actually increased by several db the loudness of speech presented only to the opposite ear. If the noise was above a certain intensity, however, some 70 to 90 db above its threshold of audibility, the noise reduced the loudness of the speech signal in the opposite ear.

[6]As this report was being prepared for press, the following article appeared: Bolt, R. H. and MacDonald, A. D. Theory of speech masking by reverberation. *J. acoust. Soc. Amer.*, 1949, 21, 577-580. The authors develop a general statistical theory for the masking effect of reverberation on speech intelligibility. It was found that values of speech intelligibility as a function of reverberation time calculated on the basis of their theory agrees well with experimental values presented previously by Knudsen, V. O. *Architectural Acoustics.* New York: John Wiley and Sons, 1932.

In general, noise will have little effect on the intelligibility of speech provided the long average intensity of speech is 18 db more intense than the noise throughout the frequency range from 200 to 7000 cps. The 'Articulation Index' is valid, however, only with certain types of noise. Also, in its computation, such significant factors as amplitude distortion, interaural phase relations, reverberation, and others, are not taken into account.

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Appendix

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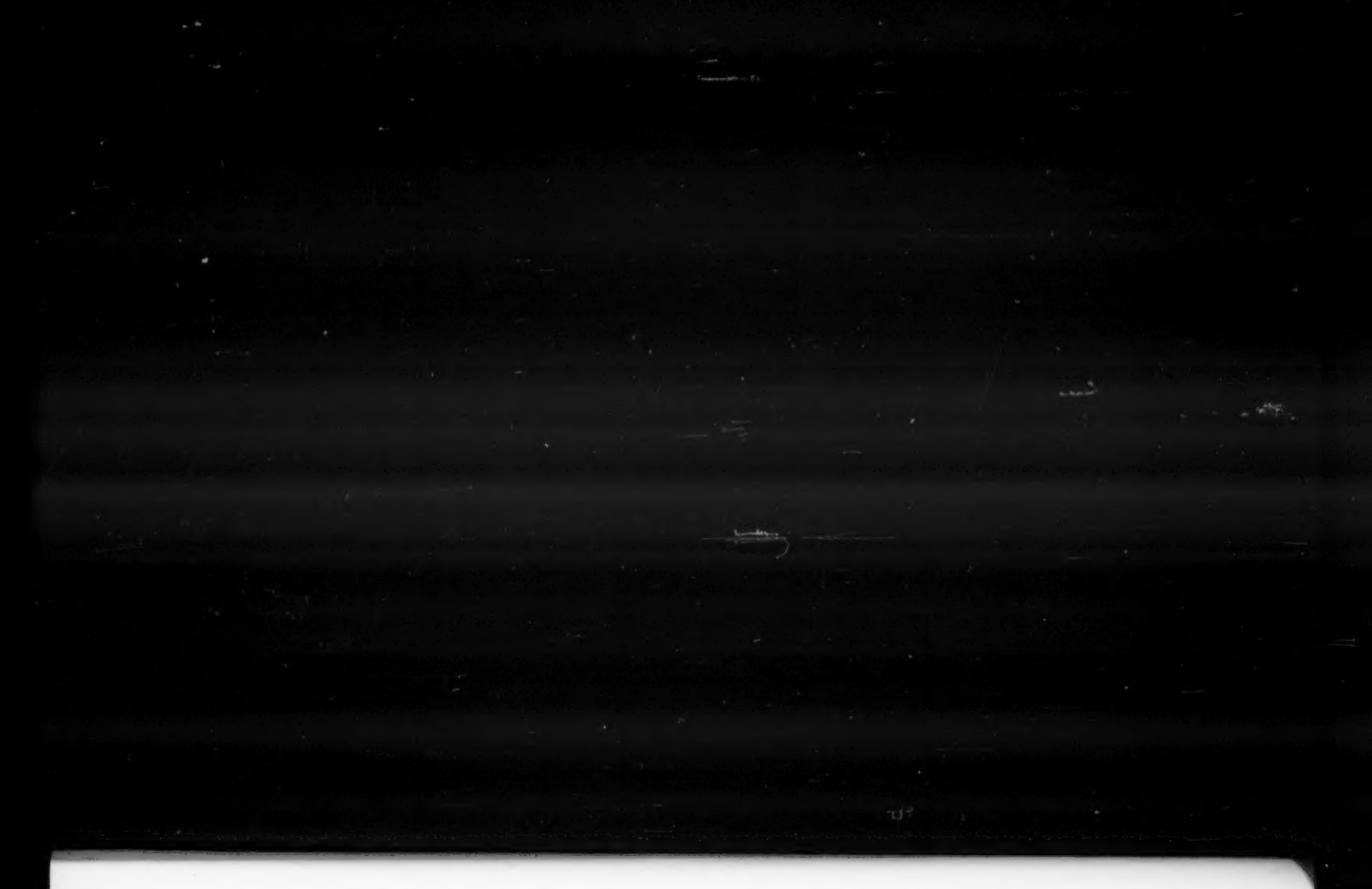
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